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Conference 8806: Metamaterials: Fundamentals and Applications VI

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SPIE Optics+Photonics NanoScience + Engineering

8806-1, Session 1

Generalized transformation media: it's all geometry! *(Keynote Presentation)*

Martin W. McCall, Imperial College London (United Kingdom)

The programme of Transformation Optics is known to be exact – invariance of Maxwell's equations under deformation of the underlying manifold prescribes an exact medium recipe for the actual shaping of the electromagnetic field. Why the programme is quite so uniquely successful for electromagnetics is still somewhat unclear (although we have an excellent candidate conjecture that concisely captures the mathematical features of electromagnetism that do not carry over to acoustics and water waves , for example). Therefore, if we wish to develop a generalised approach for transformation media, we must descend from the exact field equations to more approximate theories that have common characteristics with other physical theories. The most promising level of attack appears to be at the level of rays. The prescription for ray behavior develops the rays for a given index distribution. However, the converse problem of finding an index distribution for a given ray deformation can only be given for conformal transformations. Despite this apparently severe restriction, significant generalization is possible when the transformation is into a space that is characterized by an anisotropic metric. We can then achieve an inversion for any desired ray deformation, in principle applicable to a wide class of physical systems, such as acoustics, Schrodinger waves, thermal waves, water waves, and so on. Any context can be addressed, in fact, where an anisotropic "index" can be defined as the directed ratio of a flux to an energy density. Being formulated geometrically also means we are no longer tied to an underlying Euclidean space, and can use our approach to design a cloak on a sphere, for example. Our methodology also accesses quantitatively the relationship between the desired deformation and the induced Riemanian curvature, which, in turn, accesses the criteria for making black holes, white holes, concentrators and a host of other useful devices. The talk will be of general appeal and be set the context of historic cloaking paradigms such as the Pendry/Leonhardt spatial cloak, and, of course, the spacetime cloak.

8806-2, Session 1

Transforming optical forces *(Invited Paper)*

Vincent Ginis, Vrije Univ. Brussel (Belgium); Philippe Tassin, Iowa State Univ. (United States) and Chalmers Univ. of Technology (Sweden); Costas M. Soukoulis, Iowa State Univ. (United States); Irina P. Veretennicoff, Vrije Univ. Brussel (Belgium)

In the interaction between light and matter, linear momentum can be transferred from electromagnetic waves to particles to generate so-called optical forces. Recently, it has been suggested that optical gradient forces can be used to actuate nanophotonic devices. The typical setup consists of two waveguides positioned in each other's vicinity such that they are coupled through the interaction of the evanescent tails. Although the gradient forces between these waveguides can be enhanced considerably with the use of electromagnetic resonators, the resulting displacements remain relatively small. In this contribution, we suggest the use of metamaterials to amplify optical gradient forces. The parameters of the metamaterials are calculated using transformation optics. This technique allows approaching electromagnetic problems from a geometric perspective as it offers an equivalence relation between a transformation of the underlying coordinate system and the material parameters of a metamaterial. Here, we design metamaterials to create the illusion for the electromagnetic fields that the two slab waveguides are positioned at a smaller separation distance from each other. Indeed, optical forces between two waveguides decay exponentially with the separation distance between the waveguides. Therefore, a coordinate transformation that alters the distance between the waveguides also alters the resulting optical forces. To enhance the forces between two waveguides, the distance should be diminished. This can be achieved with a folded coordinate transformation, which translates automatically into an anisotropic metamaterial with negative components in the permittivity and permeability tensors. In this way, metamaterials can support optical forces enhanced by more than 200 times.

8806-3, Session 1

A broadband negative index metamaterial at optical frequencies *(Invited Paper)*

Jennifer A. Dionne, Stanford Univ. (United States)

A broadband metamaterial capable of negatively refracting light across the entire visible and near-infrared spectrum would enable unprecedented manipulation of light, but has to date remained elusive. In this presentation, we introduce a straightforward approach for the design of metamaterials with optical properties that are largely insensitive to the wavelength, orientation and polarization of incident light. Extending a previously described conformal transformation, we transform an infinitely extended periodic metal-insulator-metal waveguide, known to support both capacitive and inductive modes, into a metallodielectric crescent that exhibits both electric and magnetic resonances.

By calculating the phase and amplitude of light transmitted through periodic arrays of crescents, we determine that negative refractive indices can be achieved over a broad spectral range, spanning bandwidths exceeding 200 nm at visible and near-infrared frequencies. The metamaterial shows an isotropic response over a broad range of incident angles, and near-isotropicity with respect to the polarization of incident light. Furthermore, the index of the material can be tuned from layer to layer by changing the relative orientations of the crescents within each layer. We confirm the metamaterial response using simulations of plane wave refraction through a metamaterial prism, and experimentally explore such metamaterials with cathodoluminescence spectroscopy. Our results illustrate the power of transformation optics for new metamaterial design and provide a foundation for future broadband metamaterial devices.

8806-4, Session 1

All-dielectric cloaking structures: design and stereolithographic fabrication

Yaroslav A. Urzhumov, Nathan Landy, Duke Univ. (United States); Tom Driscoll, Duke Univ. (United States) and Univ. of California, San Diego (United States); Dimitri N. Basov, Univ. of California, San Diego (United States); David R. Smith, Duke Univ. (United States) and Ctr. for Metamaterials and Integrated Plasmonics (United States)

We report stereolithographic (STL) polymer-based fabrication and experimental operation of a microwave X-band cloaking device. The device is a relatively thin (about one wavelength thick) shell of an air-dielectric composite, in which the dielectric component has negligible loss and dispersion. In a finite band (9.7-10.1 GHz), the shell eliminates the shadow and strongly suppresses scattering from a conducting cylinder of six-wavelength diameter for TE-polarized free-space plane waves. The device does not require an immersion liquid or conducting ground planes for its operation. The dielectric constant of the polymer is low enough (2.45) to suggest that this cloaking technique would be suitable for higher frequency radiation, including visible light.

In this report, we present a general design and fabrication methodology that yields two-dimensional microwave cloaks composed of only one, virtually lossless, dispersionless, dielectric medium with epsilon=2.45. The cloaks are multidirectional, i.e. invisible with respect to several propagation directions, are capable of hiding objects many wavelengths in diameter, and are thinner relative to the object size than in any previous experimental demonstrations. Using a 2D field mapping apparatus, we measure the scattered electric field in the Fresnel zone of the structure. Visibility of the structure is reduced at optimal frequency by as much as four times relative to an uncloaked cylinder, and 5 times relative to a PEC cylinder coated with a solid ABS shell of the same thickness as the cloak. A far field calculation confirms that the cloak has strongly reduced visibility in the Fraunhofer diffraction zone.

8806-5, Session 1

Experimental demonstration of birefringent transformation optics devices

Vera N. Smolyaninova, Kurt Ermer, Alex Piazza, David Schaefer, Towson Univ. (United States); Igor I. Smolyaninov, BAE Systems (United States)

Transformation optics (TO) has recently become a useful methodology in the design of unusual optical devices, such as novel metamaterial lenses and invisibility cloaks. Very recently Danner et al. have suggested theoretical extension of this approach to birefrigent TO devices, which perform useful and different functions for mutually orthogonal polarization states of light. Theoretical designs which operate as invisibility cloak for one polarization while behaving as a Luneburg lens for another orthogonal polarization have been suggested. Here we report the first experimental realization of similar birefrigent TO designs based on lithographically defined metal/dielectric waveguides. Adiabatic variations of the waveguide shape enable control of the effective refractive indices experienced by the TE and TM modes propagating inside the waveguides. We have studied wavelength and polarization dependent performance of the resulting birefrigent TO devices. These novel optical devices considerably extend our ability to control light on submicrometer scales.

8806-6, Session 2

Natural hyperbolic materials: spatial dispersion and related phenomena *(Invited Paper)*

Evgenii E. Narimanov, Purdue Univ. (United States)

Materials with hyperbolic dispersion, the strongly anisotropic media where the dielectric permittivity tensor components has different signs in two orthogonal directions, support propagating waves with wavenumbers unlimited by the frequency. The resulting broad bandwidth singularity in the photonic density of states, with resulting manifestations in a variety of phenomena, from spontaneous emission to light propagation and scattering.

As the magnitude of the photonic density of states in hyperbolic media is limited by the wavenumber cut-off defined by the inverse unit cell size, the effect is particularly strong in natural hyperbolic materials, as compared to nanostructured composites. Furthermore, in this case the nonlocality of electromagnetic response of the medium, which normally only leads to small corrections on the order of the ratio unit cell size to the propagation wavelength, has a dramatic effect on the system - leading to formation of new hyperbolic bands and enhanced radiative thermal transport.

8806-7, Session 2

Analytical description of optical nonlocalities in nanowire metamaterials *(Invited Paper)*

Viktor A. Podolskiy, Brian Wells, Univ. of Massachusetts Lowell (United States); Anatoly V. Zayats, King's College London (United Kingdom)

Plasmonic nanorod arrays have emerged as candidates for new generation of biosensors, perfect absorbers, sub-wavelength light guides, and super-focusing systems. Plasmonic response, underlying the macroscopic properties of nanowire systems, results in collective resonance of the structures. In the proximity to the plasmonic resonance, effective permittivity of the system becomes vanishingly small. The composite nature of nanowire metamaterial results in strong nonlocality of its dielectric response in the vicinity to its epsilon-near-zero frequency.

In contrast to local uniaxial materials, nonlocal metamaterial supports not two but at least three waves, two of which have identical TM polarization. The light incident on the nanowire slab couples into both TM polarized modes. In this work we demonstrate that the two TM-polarized modes result from strong coupling between between plasmon-type electron oscillation perpendicular to metallic wires and polariton-type mode propagating along the wires. We further develop quantitative description of this coupling, mapping the solution of Maxwell equations to the coupled-oscillator model. This process yields analytical description of dispersion of optical modes inside nonlocal metamaterial.

Finally, we use homogenization of Maxwell equations at the metamaterial scale to develop a set of additional boundary conditions describing the coupling between plane-wave-type modes propagating in nanowires and in surrounding media. The results of the developed nonlocal transfer-matrix formalism are in agreement with finite-element 3D solutions of Maxwell equations.

8806-8, Session 2

Control of Förster energy transfer with density of photonic states

Thejaswi U. Tumkur, John K. Kitur, Carl E. Bonner Jr., Norfolk State Univ. (United States); Evgenii E. Narimanov, Purdue Univ. (United States); Mikhail A. Noginov, Norfolk State Univ. (United States)

We show that media with high densities of photonic states such as metals and metamaterials serve as platforms to control the rate of Förster energy transfer. Moreover, the same high density of photonic states-environments which enhance spontaneous emission, inhibit Förster energy transfer between donor and acceptor molecules. Our finding supports the possibility of controlling Förster energy transfer by metamaterials, cavities and plasmonic environments.

8806-9, Session 2

Characterization of the optical topological transition in 1D (multilayer) and 2D (nanowire) hyperbolic metamaterials

Ward D. Newman, Srikrishna Bodepudi, Minchang Zhang, Ryan Starko-Boes, Huan Hu, Jonathan Atkinson, Ilya A. Utkin, Robert Fedosejevs, Ray G. DeCorby, Sandipan Pramanik, Zubin Jacob, Univ. of Alberta (Canada)

In this work, we present the first unified approach to the design, fabrication and characterization of both 1D (multilayer) and 2D (nanowire) hyperbolic metamaterials (h-MMs). We discuss some of the common problems with reliable fabrication of multilayer and nanowire h-MMs and finally show experimental extraction of multilayer and nanowire effective medium parameters from reflection and transmission measurements.

Our approach to extracting the effective medium parameters relies on isolating the poles and zeros of the dielectric tensor predicted by effective medium theory (EMT). We show the existence of a Reststrahelen band for propagating waves and anti-Reststrahlen band for evanescent waves in the theoretical EMT response and experimental data.

An optical topological transition (OTT) in h-MMs occurs when the topology of the iso-frequency surface transitions from a closed ellipsoid to an open hyperboloid. We experimentally characterize the OTTs

in h-MMs which occurs at the epsilon-near-zero crossing and study the lifetime, absorption spectrum and emission spectrum of organic dye molecules (Alq3 and R6G) near h-MMs. 1D multilayer h-MMs are realized by fabricating alternating nanoscale layers of silver (15nm) and silica (30nm) via electron-beam evaporation. 2D h mms consist of a well-ordered array of vertically oriented silver nanowires embedded in an anodic aluminum oxide (AAO) matrix. Such structures are synthesized by combining an electrochemical self-assembly process with electrodeposition technique. Structural parameters of such 2d h mm s can be tuned by the self-assembly parameters and for this study nanowire diameter is ~30nm, length ~ 500nm and inter nanowire spacing is ~60nm.

8806-10, Session 2

Control of spontaneous emission spectra by hyperbolic metamaterials

Lei Gu, Thejaswi U. Tumkur, Guohua Zhu, Mikhail A. Noginov, Norfolk State Univ. (United States)

High density of photonic states in metamaterials with hyperbolic dispersion is known to enhance spontaneous emission rates. At this time, we demonstrate that hyperbolic metamaterials can control emission spectra as well. Experimentally, DCM and R6G dyes were embedded into lamellar metal/dielectric metamaterials. The observed ≈18 nm blue shift of emission is explained by strong dispersion of the density of photonic states. On the other hand, practically no spectral shifts were observed in the excitation spectra of the same dyes. This implies different effect (or an absence of the effect) of the density of photonic states on absorption than on emission.

8806-11, Session 3

Optic spin hall effect at metasurfaces *(Invited Paper)*

Xiang Zhang, Univ. of California, Berkeley (United States)

The relativistic spin-orbit coupling of electrons results in intrinsic spin precessions and therefore spin-polarization-dependent transverse currents, leading to the observation of spin Hall effect (SHE) and the emerging field of spintronics. The coupling between charge's spin degree of freedom and its orbital movement is essentially identical to the coupling of the transverse electric and magnetic components of a propagating electromagnetic filed. To conserve total angular momentum, an inhomogeneity of material's index of refraction can cause momentum transfer between the orbital and the spin angular momentum of light along its propagation trajectory, resulting in a transverse splitting in polarizations. Such a photonic spin Hall effect (PSHE) was recently proposed theoretically to describe the spin-orbit interaction, the geometric phase, and the precession of polarization in weakly inhomogeneous media as well as the interfaces between homogenous media. Here we demonstrate experimentally the strong interactions between the spin and the orbital momentum of light in a thin metasurface ? a two-dimensional electromagnetic nano-structure with designed in-plane phase retardation over the wavelength scale. In such an optically thin material, the resonance-induced anomalous “skew-scattering” of light destroys the axial symmetry of the system and we observed PSHE even at the normal incidence. In stark contrast, for conventional interfaces between two homogeneous media, the spin-orbit coupling does not exist at the normal incidence.

8806-12, Session 3

Device applications of metafilms and metasurfaces *(Invited Paper)*

Mark Brongersma, Geballe Lab. for Advanced Materials (GLAM) (United States)

Many conventional optoelectronic devices consist of thin, stacked films of metals and semiconductors. In this presentation, I will illustrate how one can improve the performance of such devices by nano-patterning the constituent layers at length scales well below the wavelength of light. The resulting metafilms and metasurfaces offer opportunities to dramatically modify optical transmission and reflection properties and enhance light-matter interactions. To illustrate these points, I will show how nanopatterned metals and semiconductor layers can be used to enhance the performance of photodetectors and solar cells.

8806-13, Session 3

Holographic metasurfaces *(Invited Paper)*

Patrice Genevet, Harvard School of Engineering and Applied Sciences (United States); Jiao Lin, A*STAR (Singapore); Jean Dellinger, Benoit Cluzel, Univ. de Bourgogne (France); Mikhail A. Kats, Harvard School of Engineering and Applied Sciences (United States); Frédérique A. de Fornel, Univ. de Bourgogne (France); Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

Plasmonic gratings and plasmonic lenses are routinely used to convert free-space beams into propagating surface waves and vice versa. So far, this approach has been limited to simple light beams, such as plane waves or Gaussian beams. I will present a powerful generalization of plasmonic structures to couple more complex wavefronts. This approach is based on the principle of holography: the coupler is designed as the interference pattern of the incident vortex beam and focused SPPs. We have integrated these holographic plasmonic interfaces into commercial silicon photodiodes, and demonstrated that such devices can selectively detect the orbital angular momentum of light. We also introduced, the cosine-Gauss beam, which does not diffract while it propagates in a straight line and tightly bound to the metallic surface. The generation of this highly localized wave is shown to be straightforward and highly controllable, with varying degrees of transverse confinement and directionality, by fabricating a plasmon launcher consisting of intersecting metallic gratings. By analogy to the three dimensional optical bottle beams, we introduce a two dimensional surface wave which features oscillating dark focuses surrounded by regions of higher intensity. This beam is a created by superposing the two-dimensional nondiffracting cosine-Gauss beam, characterized by a constant on-axis slow phase velocity, and a quasi-plane wave. This approach might find interesting applications in plasmonic trapping, by creating two dimensional arrays of intensity hot spots in the close vicinity to metallic interfaces.

8806-14, Session 3

Experimental validation of a new bianisotropic parameter retrieval technique using plasmonic metasurfaces made of V-shape antennas

Jingjing Liu, Amr M. Shaltout, Purdue Univ. (United States); Xingjie Ni, Purdue Univ. (United States) and Univ. of California, Berkeley (United States); Vladimir M. Shalaev, Alexander V. Kildishev, Purdue Univ. (United States)

We report on an experimental and theoretical study of Babinet's principle for v-shape antenna metasurfaces at optical frequencies. Large dimension arrays of nano-voids are fabricated using electron beam lithography. Experiments demonstrate that angular positions of diffracted cross-polarized light are the same for the regular and Babinet-inverted design. Furthermore, the Babinet-inverted design greatly increases the extinction ratio. Also, each antenna element with a discrete phase shift is modeled by a homogenous bianisotropic film to represent the optical response. We find a complementary relationship in the effective permittivity. This relationship gives a correspondence between the spectral positions of the eigenmodes and the positions of the effective permittivity resonances. It also explains the observations that the best performing wavelength of cross-polarized scattered light is blue shifted for the complementary design compared to its regular counterpart. Since the effective bianisotropic parameters of each antenna element produce the same response to incident plain waves as the full-wave simulations, theoretically we could unite different elements to compose a patch antenna array which forms a metasurface capable of bending the light abnormally. It provides a shortcut to observe the coupling effects between adjacent antennas and to simulate the response of the whole device. Simulations show that two adjacent antennas will couple with each other so that the final design does not have the same local response as a single antenna. The experiments also show that the device has a high extinction ratio when the coupling effect is weak.

8806-15, Session 4

Graphene metamaterials *(Invited Paper)*

Javier García de Abajo, ICFO-Institut de Ciencies Fotoniques (Spain)

Graphene offers great opportunities as a novel platform for electrically tunable, ultrathin metamaterials. We will review recent advances and opportunities in the field of graphene metamaterials, including applications to optical modulations and sensing.

8806-16, Session 4

Time domain modeling of metasurfaces with graphene *(Invited Paper)*

Ludmila J. Prokopeva, Alexander V. Kildishev, Naresh K. Emani, Purdue Univ. (United States); Alexandra Boltasseva, Purdue Univ. (United States) and Technical Univ. of Denmark (Denmark)

Graphene is an interesting elemental material due to the properties of its dielectric function. Permittivity of graphene depends on chemical potential and temperature and can be electrically controlled by the applied bias voltage, [1-3]. Thus, the transmission of a bare graphene sheet can be changed by approximately 1% by applying a gate voltage, see [2-3]. Further, it has been shown that with local field enhancement the induced change can be as high as 30% for resonance frequency of bowtie antenna metasurface [2]. A time-domain phenomenological parametric model of the tunable dielectric function of graphene is imperative for accurate numerical simulations of time-resolved multiphysics, including studies of nonlinear optical response of grahene-based tunable photonic devices with metamaterials or metasurfaces. However, precise time domain modeling of graphene is complicated with the integral expressions of dielectric function. Integrals have to be accurately approximated and effectively evaluated numerically for broadband wavelength operation within desired ranges of tunable parameters such as chemical potential and temperature.

In this paper an accurate causal broadband time domain model for optical response of graphene, consisted of the Drude term and a number of critical point terms, is presented [4]. The model can be used for time domain simulations with FDTD, FETD, FVTD Maxwell's solvers. Example applications of time-domain modeling of the graphene-based tunable devices are discussed.

[1] A. Grigorenko, M. Polini, and K. Novoselov, "Graphene plasmonics," Nature Photonics 6, 749-758 (2012).

[2] N. K. Emani, T.-F. Chung, X. Ni, A. V. Kildishev, Y. P. Chen, and A. Boltasseva, "Electrically Tunable Damping of Plasmonic Resonances with Graphene," Nano Letters 12, 5202-5206 (2012).

[3] L. Ju et al. "Graphene plasmonics for tunable terahertz metamaterials", Nat. Nanotechnol. 6, 625-629 (2011).

[4] P. G. Etchegoin, E. C. Le Ru, and M. Meyer, "An Analytic Model for the Optical Properties of Gold," J. Chem. Phys. 125, 164705 (2006).

8806-17, Session 4

Time-domain multiphysics of silver nanowires-graphene transparent conducting electrodes

Jieran Fang, Suprem R. Das, Ludmila J. Prokopeva, Vladimir M. Shalaev, David B. Janes, Alexander V. Kildishev, Purdue Univ. (United States)

It has been already shown that transparent conducting electrodes (TCE) constructed of silver nanowires (SNW) co-percolated with a single-layer graphene (SLG) cover have higher optical transparency and lower sheet resistance than commercially-available ITO and are comparable to the best reported results in TCEs [1]. Numerical analysis of the multiphysics of SNW-SLG electrodes is built on the broadband 3D FDTD simulations, coupled to auxiliary equations describing the optical responses of the SLG cover and a layer of randomly distributed SNW.

To approximate the dielectric function of SLG we fit the Drude – Continuous Critical points (DCCP) model [2] to the experimental transmittance and reflectance data from SLG samples. The numerical implementation of the individual terms of the DCCP model follows [3].

Bare and SLG-covered random SNW layers are simulated using the spectral averaging of the FDTD transmittance and reflectance data from individual indiscriminately selected frames [4]. Numerical simulations are done for a number of frames until a convergent set of averaged spectra is obtained. Details and future trends of these experiment-fit simulations are discussed.

[1] R. Chen et al., "Co-percolating Graphene-Wrapped Silver Nanowire Network for Record Performance, Highly Stable, Transparent Conducting Electrodes," Advanced Functional Materials (submitted).

[2] L. Prokopeva et al., "Time Domain Modeling of Metasurfaces with Graphene", CLEO 2013 (submitted).

[3] L. Prokopeva et al., "Optical dispersion models for time-domain modeling of metal-dielectric nanostructures", IEEE Trans. on Magn. 47, 1150-1153 (2011).

[4] J. Fang et al., "Numerical studies on randomly distributed gold nano-net structures,"27th ACES conference (2012).

8806-300,

Molding Optical Wavefronts: Flat Optics Based on Metasurfaces

Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

Metasurfaces based on sub-wavelength patterning have major potential for realizing arbitrary control of the wavefront of the diffracted light by achieving local control of the phase amplitude and polarization. We discuss novel devices based on this technique; a salient feature is the ability to create often with a single digital mask an arbitrary analog phase profile. A variety of flat optical components, including lenses, polarizers, vortex plates, coatings, holograms and couplers with polarization invariant coupling efficiency will be presented.

8806-301,

From Photonic Metamaterials to Metadevices: Exploiting Forces and Fields at the Nanoscale

Nikolay I. Zheludev, Univ. of Southampton (United Kingdom) and Nanyang Technological Univ. (Singapore)

Metamaterials, artificial electromagnetic media achieved by structuring on the subwavelength scale, were initially suggested as negative index

media for the "superlens" and for transforming electromagnetic space to control propagation of waves. The research agenda is now shifting to achieving tunable, switchable, nonlinear and sensing functionalities using metamaterails. We show how engaging the changing balance of forces, structural transformation, light confinement and quantum effects at the nanoscale bring about the emerging field of metadevices. We define metadevices as devices with unique and useful functionalities achieved by structuring of functional matter on the subwavelength scale.

8806-302,

Recent Progress in Photonic Crystals

Susumu Noda, Kyoto Univ. (Japan)

I will talk about recent progress in photonic crystals. First of all, I will discuss on the progress in 2D photonic crystals, where the focus is on the thermal emission control which is important for energy harvesting. Next, I will discuss about on-demand 3D guiding of photons in 3D photonic crystals, which have been a long dream. Then, I will describe the other interesting topics, including ultrahigh-Q nanocavities, stopping light, ultra-small Si Raman lasers, SiC photonics, unique 2D lasers, etc.

8806-18, Session 5

Low-loss localized surface phonon polariton modes in silicon carbide nanopillars: beyond plasmonics *(Invited Paper)*

Joshua D. Caldwell, U.S. Naval Research Lab. (United States); Yan Francescato, Imperial College London (United Kingdom); Orest J. Glembocki, U.S. Naval Research Lab. (United States); Nicholas Sharac, Univ. of California, Irvine (United States); Francisco J. Bezares, U.S. Naval Research Lab. (United States); Vincenzo Giannini, Imperial College London (United Kingdom); James P. Long, Jeffrey C. Owrutsky, Joseph G. Tischler, Igor Vurgaftman, U.S. Naval Research Lab. (United States); Stefan A. Maier, Imperial College London (United Kingdom); Virginia D. Wheeler, Loretta Shirey, Nabil D. Bassim, U.S. Naval Research Lab. (United States); Richard Kasica, National Institute of Standards and Technology (United States); Chase Ellis, U.S. Naval Research Lab. (United States)

Over the past decade, significant effort has been focused on the field of plasmonics and its applications in enhanced spectroscopy, light emitters, waveguides, and absorbers for photodetectors. However, while plasmonic systems have attracted attention for their ability to achieve extreme sub-diffraction limit confinement with large concentrations of optical energy, they are severely limited by the inherent ohmic losses due to the high carrier densities within metals. Therefore, it is desirable to identify new materials capable of supporting electromagnetic modes below the diffraction limit without excessive loss. We report on the observation of localized surface-phonon (SPhP) polariton resonances in 800-nm-tall nanopillars fabricated from semi-insulating 6H- and 4H-silicon carbide with diameters of 150-260 nm and 1 µm, respectively. These localized SPhP resonances exhibit exceptionally narrow linewidths of 7-24 cm< sup>-1< /sup>, corresponding to quality factors in the 40-140 range. Such high Q-factors, coupled with the small modal volumes that are 15-50x smaller than the incident wavelength, result in what is to our knowledge the highest potential Purcell factors reported to date for nanoscale resonators, with values between (2-7)x10< sup>5< / sup>. These exceptional properties are the result of the long lifetimes of the optical phonons supporting these oscillations. The performance of these initial structures point to what is possible with SPhP systems. With SiC in particular, these resonances should prove useful for military and commercial applications because they occur in the 8-12 µm, infrared atmospheric window, which also overlaps the spectral band of a wide array of molecular vibrations.

8806-19, Session 5

Non-Hermitian plasmonics *(Invited Paper)*

Pavel Ginzburg, Anatoly V. Zayats, King's College London (United Kingdom)

Optical properties of plasmonic nanostructures may exhibit counterintuitive manifestations of the dissipative dynamics of the inherently lossy electron system of a metal. Their dissipative evolution can be described within non-Hermitian formulation of quantum mechanics. Here, we will overview recent theoretical approaches to dissipation in plasmonic systems. Based on these non-Hermitian theories, we will discuss plasmonic analogues of some quantum effects and their applications in photonics, concentrating on quantum Hanle effects due to dissipative coupling in plasmonic metamaterials, and non-Markovian dynamics of plasmonic dark modes. In the standard quantum Hanle effect, time-reversal symmetry is broken by a static magnetic field. We will show that similar effect in plasmonics could be achieved by introducing dissipative level crossing of localized surface plasmons due to nonuniform losses, designed using a non-Hermitian formulation of quantum mechanics. Such metamaterial has been shown to exhibit strong circular birefringence and circular dichroism which depends on the value of loss or gain in the metal-dielectric nanostructure. It will also be shown that the dynamics of the weakly coupled to radiation (dark) modes of subwavelength plasmonic nanostructures may be strongly nonexponential and their lifetime can be overestimated by conventional exponential relaxation time obtained in the standard Markovian approximation.

1. P. Ginzburg and A. V. Zayats, "Non-exponential decay of dark localized surface plasmons," Opt. Express 20, 6720-6727 (2012).

2. P. Ginzburg, F. Rodriguez-Fortuno, A. Martinez, and A.V. Zayats, "Analogue of the Quantum Hanle Effect and Polarization Conversion in Non-Hermitian Plasmonic Metamaterials", Nano Lett., 12 (12), 6309–6314 (2012).

8806-20, Session 5

Optical metamaterials based on plasmonic nanoparticle chains *(Invited Paper)*

Koray Aydin, Northwestern Univ. (United States)

Metal nanostructures support localized plasmon resonances at optical frequencies that can be controlled by changing their size, shape and dielectric permittivity of the environment. The field of plasmonics is dedicated to the study of optical properties of various metal nanostructures including chemically synthesized metal nanoparticles (bottom-up), as well as top-down fabricated metallic gratings, antennas and nanostructure arrays. Similarly, optical metamaterials are composed of metal nanostructures with unique geometries, therefore facilitating localized electric and/or magnetic resonances. Initially, the fields of plasmonics and metamaterials progressed as two separate disciplines with little overlap. However, after the realization of optical metamaterials using plasmonic (gold and silver) nanostructures, the interactions between these two fields of nanoscience increase drastically. In this talk, I will describe novel metamaterial building blocks that are composed of gold nanoparticles rather than top-down fabricated conventional metamaterial elements. Comparisons will be made with conventional metamaterials and nanoparticle based metamaterials. Our simulations predict drastic red-shift of metamaterial resonances of optical-antenna and split-ring resonator shaped nanoparticle chains due to increased effective inductance. Nanoparticle chain metamaterials operate at a broader wavelength range, are much smaller than corresponding continuous metal-bar shaped resonators, are less lossy and have higher localized electric fields, making them attractive for a variety of applications including sensing, light-trapping, and optical filters.

8806-21, Session 5

Functional nanostructures for plasmonic sensing and energy applications *(Invited Paper)*

Wei Ting Chen, Ming Lun Tseng, Yao-Wei Huang, Pin Chieh Wu, National Taiwan Univ. (Taiwan); Kuang-Yu Yang, Academia Sinica (Taiwan); Chia Min Chang, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan); Bo Han Cheng, Yen Ju Liu, Academia Sinica (Taiwan); Yueh-Hung Cheng, Chun Yen Liao, Hung-Kuei Tsai, Kuang Sheng Chung, Yu Lin Chen, National Taiwan Univ. (Taiwan); Hung Yi Chung, Academia Sinica (Taiwan); Yung-Chiang Lan, National Cheng Kung Univ. (Taiwan); Ding-Wei Huang, National Taiwan Univ. (Taiwan); Ai Qun Liu, Nanyang Technological Univ. (Singapore); Din Ping Tsai, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan)

In this talk, we give some practical applications such as molecular sensing, and photocatalytic water splitting that based on plasmonic nanostructures. The plasmonic nanostructures can be achieved via fs-laser direct writing and laser induced forward transfer techniques with high-throughput [1]. We demonstrated the surface-enhanced Raman scattering measurement (SERS) of molecules on Ag nanostructures and shown the high intensity that resulting from fine plasmonic enhancements and identical plasmonic hotspots, the processed AgOx thin films exhibit broad-band enhancement of optical absorption and effectively function as active SERS substrates. Probing of the plasmonic hotspots with dyed polymer beads indicates that these hotspots are uniformly distributed over the treated area [2]. We will also show that the AgOx thin film treated by fs-laser, which can be used as plasmonic layer to enhance the efficiency of photocatalytic process [3]. The photocurrent of ZnO/Ag plasmonic photoelectrode shows an 85 % enhancement in comparison with the photocurrent of ZnO photoelectrode only. Both localized surface plasmon resonance in metal nanoparticles and plasmon polaritons propagating at the metal/semiconductor interface are available for improving the capture of sunlight and collecting of charge carrier. Furthermore, in-situ X-ray absorption spectroscopy was performed to monitor the plasmonic-generating electromagnetic field upon the interface between ZnO/Ag nanostructures as well. This can reveal inducing vacancies on conduction band of ZnO, which allow effectively separating charge carriers and improve the efficiency of hydrogen generation. Plasmon-induced effects simultaneously enhanced the photoresponse, by both improving optical absorbance and facilitating the separation of charge carriers. These results offer a low-cost and high-efficiency approach to develop plasmonic nanostructures for sensing and energy applications.

8806-22, Session 5

Applications of plasmonic nanostructures for linear and nonlinear optics *(Invited Paper)*

Augustine M. Urbas, Vitaliy Pustovit, Dean P. Brown, Air Force Research Lab. (United States)

Abstract- Metamaterials in optical frequencies have a tremendous range of application, many of which require large area materials with fine features. Self assembly can provide an efficient route to fabricating structured optical metamaterials. From enabling fundamentally new effects, such as optical magnetism, to creating tailored absorption and transmission spectra, designing optical properties through structure offers a new mechanism for manipulating light. These systems require nanometric features on structures frequently below 100nm in size in order to gain the desired properties set. Various approaches can be used to create these structures and incorporate active materials into them for device applications. Self assembled systems can be used either directly as metamateials or as templating structures to create ordered arrays of meta-atoms. In addition, these techniques can be applied at the unit cell level to create complex, structured and active metamaterials. In this presentation, I will describe efforts to utilize self assembly techniques to create optical metamaterials. Systems designed to control fluorescence, nonlinear properties and optical absorption will be discussed. Based on the properties and local field control offered by these structures, I will also explore applications which can benefit from optical nanostructures, such as enhanced detectors

8806-23, Session 5

Raman plasmons in metal nanostructures

Andrey K. Sarychev, Institute for Theoretical and Applied Electrodynamics (Russian Federation); Sergei O. Boyarincev, Moscow Institute of Physics and Technology (Russian Federation)

We consider local optical field in the systems of metal nanoparticles. In particular, we are interested in the local electric field in the metal clusters and aggregates that have fractal structure. The metal fractals are formed, for example, in the semicontinuous metal film and in colloidal suspensions of metal nanoparticles. The light excites surface plasmons in the metal fractal and the system operates as a set of plasmon nanoantennas. Localization of plasmons results in giant fluctuation of the local electric field. Consider the Raman active molecules deposited on the metal particles. The molecules are excited by plasmons and operate as incoherent sources of the secondary electromagnetic field, which frequency is different from the frequency of the prime field by the Stokes shift. Thus, we obtain the surface enhanced Raman scattering (SERS) but also the plasmons excited by the dipoles of the Raman molecules. We use the original computer method to calculate the field of Raman plasmons in various fractals. It appears that the Raman plasmon is localized near the fractal. The fluctuations of the Raman local electric field are even larger than fluctuations of the primary field. Moreover, the spatial correlation functions of the Raman plasmons in the metal fractals are different from that of the prime plasmons. We find the distribution of the Raman plasmons in semicontinuous metal films and metal aggregates and show that these plasmons can be observed in the nearfield experiment.

8806-24, Session 6

Electric and magnetic dipole radiation in hyperbolic metamaterials *(Invited Paper)*

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Hyperbolic medium is a uniaxial medium where the longitudinal and transverse dielectric constants are of opposite signs. Its distinct feature is the hyperbolic surface of the wavevectors, corresponding to the extraordinary mode of given frequency. Specific properties of such hyperbolic materials include giant enhancement of the spontaneous emission and light-matter interaction due to the (ideally) diverging density of photonic states.

Here we focus on the Purcell enhancement of the spontaneous emission rate for both electric and magnetic dipole sources embedded in hyperbolic metamaterials. It is shown that the Purcell effect is strongly sensitive to the emitter type and orientation. We analyze different metamaterial realizations, including layered metal-dielectric structures, wire medium and arrays of split-ring resonators. Analytical estimates and numerical answers are provided for structures operating in both microwave and optical spectral ranges.

We also present comprehensive analysis of the electromagnetic Green function in hyperbolic metamaterials. Spatial distribution of the Green function has a peculiar cone-like shape. Validity of the local effective-medium approximation is examined. Additional spatial modulation of the point source emission pattern, arising due to nonlocality, is demonstrated. Interplay between the Purcell enhancement of spontaneous emission from single emitter and the Foerster resonant energy transfer between two quantum emitters is investigated for hyperbolic medium.

8806-25, Session 6

Angular distribution of emission from hyperbolic metamaterials

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Metamaterials with hyperbolic dispersion have high density of photonic states and can control spontaneous emission of molecules or quantum dots deposited on the top or embedded inside these materials. Until now, most of the studies in this area have been devoted to emission kinetics and spontaneous emission rates. At this time, we report on theoretical and experimental studies of angular distribution patterns of spontaneous emission from metamaterials with hyperbolic dispersion.

8806-26, Session 6

Collective spontaneous emission effects in semiconductor hyperbolic metamaterials

Prashant Shekhar, Zubin Jacob, Univ. of Alberta (Canada)

We show strong coupling between intersubband transitions (ISBTs) and the high-k modes of a semiconductor hyperbolic metamaterial (HMM). These high-k modes, modes with large wavevectors normally evanescent in conventional materials, can propagate in the semiconductor HMM leading to novel collective absorption and emission effects. We analyze a metal- dielectric multilayer structure consisting of a highly doped n+-InGaAs layer as the metal. Each dielectric layer consists of an Al0.35Ga0.65As and GaAs multiple quantum well slab acting as an active dielectric layer. Strong coupling and characteristic anticrossing with a maximum vacuum rabi splitting (VRS) energy of up to 104 [meV] was observed between the high-k mode of the semiconductor HMM and the ISBT, a value approximately 21 times greater than the ISBT linewidth. Strong coupling is achieved with multiple high-k modes forming a series of 'high-k-ISBT polaritons'. It is found that the magnitude of the VRS energy decreases with increasing high-k mode number and can also be tuned on and off completely by modulation of the semiconductor electron density. The spectral location of the anti-crossing behaviour, can also be pre-tuned during fabrication via control of the ISBT transition energy through the quantum well and barrier thicknesses as well as the semiconductor doping density. This scalability and tunability of the VRS energy available in semiconductor HMMs have potential applications in quantum well infrared photodetectors and tunable intersubband light-emitting devices. Our work lays the foundation for semiconductor based collective spontaneous emission and absorption processes in hMMs.

8806-27, Session 6

Optical properties of metal-dielectric based epsilon near zero metamaterials

Ganapathi S. Subramania, Sandia National Labs. (United States) and Univ. of New Mexico (United States); Arthur J. Fischer, Sandia National Labs. (United States); Ting S. Luk, Sandia National Labs. (United States) and The Ctr. for Integrated Nanotechnologies (United States)

Epsilon near zero(ENZ) materials are metamaterials where the effective dielectric constantis close to zero for a range of wavelengths resulting in zero effective displacement field (D) and displacement current. ENZ structures are of great interest in many application areas such as optical nanocircuits, supercoupling, sub-diffraction imaging, cloaking, emission enhancement etc. Effective ENZ behavior has been demonstrated using cut-off frequency region in a metallic waveguide where the modal index vanishes. Here we demonstrate the fabrication of ENZ metamaterials operating at visible wavelengths (lambda~ 640nm) using an effective medium approach based on a metal-dielectric composites. This structure is more suitable where a bulk ENZ material is required such as for etching grooves to create optical connecting 'wires' for optical nanocircuits. The structure consists of a multilayer stack composite of alternating nanoscale thickness layers of Ag and TiO2. Optical spectroscopy shows transmission and absorption response is consistent with ENZ behavior and matches well with simulations. We will discuss the criteria necessary in the design and practical implementation of the composite that better approximates a homogenous effective medium. We will also discuss techniques such as the subwavelength gratings that minimize the effect of optical losses to boost transmission. The potential for hosting gain media in the gratings to address losses as well as emission control will be discussed.

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8806-28, Session 6

Power emitted by a two-dimensional periodic array of sources at the surface of a hyperbolic metamaterial

Caner Guclu, Salvatore Campione, Filippo Capolino, Univ. of California, Irvine (United States)

Hyperbolic metamaterials (HMs) exhibit hyperbolic iso-frequency wavevector dispersion and theoretically host an unbounded spatial spectrum of waves that can propagate within the HM. However, practical realizations of HMs impose a maximum transversal propagating wavenumber. Recently, many studies demonstrated that one can achieve a propagating spectrum in HMs much wider than the spectrum of propagation in free space by using subwavelength-thick alternating layers of metals and dielectrics at infrared and optical frequencies. This unusually wide spectrum achieved in a wide frequency band is shown to enhance the emitted power by a single imposed dipole in proximity of HMs, as well as the scattered power by a nanosphere located on top of HMs. In both cases, most of the power is directed toward the HM itself. Previous experimental work showed that placing many scatterers on HMs may lead to unprecedented absorption properties. We develop here a theoretical framework to assess the capabilities and limitations of using HMs in such designs. Indeed, it is of utmost importance to model the effect of numerous sources or scatterers for the enhancement of emitted or scattered power and its redistribution toward the HM, which might lead to novel absorber designs. In this work, we investigate the power emitted by a two-dimensional periodic array of impressed sources in proximity of HMs by using an analytic approach that employs Green's functions and spectral theory. The results drawn in this study are of key importance for future work related to a periodic set of scatterers on top of HMs.

8806-30, Session 6

Enhancement of scattered power by microscatterers and near-field absorption at the surface of graphene-based hyperbolic metamaterial

Mohamed A. Othman, Caner Guclu, Filippo Capolino, Univ. of California, Irvine (United States)

Hyperbolic metamaterials (HMs) are recently studied for the enhanced absorption of near-fields generated at their surface, taking advantage of the propagating spatial spectrum in HMs which is much wider than the propagating spectrum in free space. Practical realizations of HMs at optical frequencies utilize subwavelength-thin metal-dielectric layers for enhancing the scattered power by passive nanoparticles in the vicinity of HMs, where most of the power is directed toward the HM side. Recently, graphene-based HMs comprising graphene-dielectric layers are proposed at far- and mid-infrared frequencies, taking advantage of graphene as a low loss inductive constitutive layer offering a great opportunity for controlling the hyperbolic dispersion properties via biasing with static fields, and thus designing tunable HMs. In this work, we explore the scattered power enhancement by passive microscatterers at the surface of graphene-based HM, and power absorption by the HM. Moreover we investigate the tunability of the dispersion characteristics of the graphene-based HM using both electrostatic and magnetostatic biasing, and we report the control of the scattered power enhancement. The key parameters on the HM design with graphene are discussed and their impacts on the tunability and absorption capabilities of the metamaterial are quantified. The effective parameters of the multilayers are derived for the graphene-based HM under bias and they are shown to predict the hyperbolic dispersion regime and near-field absorption features, in good agreement with the transfer matrix analysis.

8806-31, Session 6

Realistic electric field modeling of multilayered nanostructures by classic electrodynamics and first principles theory

Vladimir I. Gavrilenko, Alexander V. Gavrilenko, Norfolk State Univ. (United States); Ludmila G. Ilchenko, Vasyl V. Ilchenko, National Taras Shevchenko Univ. of Kyiv (Ukraine)

Typical metamaterial structures are composed from periodic pattern of conductive and non-conductive components. Efficient engineering of metamaterials involves modeling of electric field profiles around these structures. Realistic modeling of the electric field in metamaterials requires accurate knowledge of optical constants of the components for which traditionally the bulk values are taken. Further progress in the developing of metamaterials is characterized by a reduction of the pattern size, dimensions of single layers in multilayered structures etc. It has been understood that optical functions in low-dimensional and nano-sized materials substantially differ from their bulk values increasingly affecting by quantum processes.

In this work we develop a complex method for analytical modeling of electric field profiles in metamaterials including quantum processes in nano-sized multi-layered structures. In particular based on first principles density functional theory we obtained simple analytical functions allowing predictions the optical functions variations with the size reduction of single metamaterial components over a wide spectral region. It is shown that optical functions of nano-sized films substantially (by 50 percent and more) differ from those in bulk. The new calculated optical functions of the components are used for electric field profile modeling of nano-sized multilayered structures by nonlocal Green function technique including effects of spatial dispersion. Silicon, silicon dioxide, and water layers are used as an example. The method effectively incorporates real atomic structure reconstruction on surfaces and inner interfaces thus providing with a more realistic picture for modeling. By comparison with experiment it is demonstrated that our method predicts image potential of the nanostructures in better agreement with experiment than if using traditional classic electrodynamics approach neglecting the quantum effects. The results are discussed in comparison with literature

8806-32, Session 7

Mapping the properties of plasmonic and metamaterial structures in the near field *(Invited Paper)*

Uriel Levy, Avner Yanai, Meir Grajower, Boris Desiatov, Ilya Goykhman, Liron Stern, The Hebrew Univ. of Jerusalem (Israel)

In this talk we present our recent experimental results showing the mapping of plasmonic and metamaterial structures in the near field. For example, we will demonstrate strong heating of metallic and metallo-dielectric structures by probing the structures with a thermocouple tip in the near field. The experimental results will be explained by electromagnetic and heat simulations.

8806-33, Session 7

A characterization study of highly tailorable 3D metamaterials in the thermal infrared for selective emission behaviors

Bryan M. Adomanis, Air Force Institute of Technology (United States); D. Bruce Burckel, Sandia National Labs. (United States); Michael A. Marciniak, Air Force Institute of Technology (United States)

The spectral and directive behaviors of highly tailorable thermal infrared metamaterials were characterized between 6-20µm wavelengths and 0-50-degree incidence angles, through finite-difference time domain (FDTD) simulation and spectroscopic measurements. Sandia National Laboratories fabricated true 3-D metamaterial unit cells using the membrane projection lithography (MPL) phenomenology. The 1cm^2 samples consisted of gold bent dipoles evaporated inside 5µm cubic cavities on a 6µm pitch in an SU-8 photoresist substrate. Three samples contained bent dipoles with 5µm total length and upper/lower dipole fractions of 90/10, 50/50 and 20/80; samples with a purely vertical or purely horizontal dipole of 4µm each were also fabricated as the control. SEM images exposed significant cavity warpage in all samples, producing localized non-uniformity of the dipoles. Both measurement and simulation for multiple polarization/dipole orientation states confirmed the existence of dipole resonances, though fabrication errors led to spectral broadening and reduced intensity in measurements. For states with fields polarized parallel to the dipole moment, the dominant mode was a broad fundamental electrical mode, which compared well to simulations. A slightly weaker, sharper, higher-frequency plasmonic mode was clearly present in simulation for states with perpendicular polarizations, but was visible only in measurements which did not have dominant electrical modes. As incident angle increased, the modes shifted to longer wavelengths along the incident-angle/wavelength Bragg diffraction edge. Finally, the samples were heated to 150 degrees C and directional emittance was calculated from spectral radiance measurements, and found to be in good agreement spectrally with a Kirchoff emittance calculated from transmittance and reflectance measurements.

8806-34, Session 7

Directional thermal emission from a leaky-wave frequency-selective surface

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Carolina at Charlotte (United States); Louis A. Florence, U.S. Military Academy (United States); Brian A. Lail, Florida Institute of Technology (United States); Glenn D. Boreman, The Univ. of North Carolina at Charlotte (United States)

We designed and characterized a Frequency Selective Surface Metamaterial for directional emission at 9.8 µm. The design consists of an array of Au patch antennas and microstrips, both separated from a Au ground plane with a ZnS standoff. We patterned a 2x2 cm structure using lift-off and e-beam lithography so that the absorptance could be measured in the far-field using a hemispherical directional reflectormeter (HDR). These experimental results showed good spectral/directional agreement with Finite Element numerical simulations of the structure (Ansoft HFSS). The structure supports guided leaky-wave type modes with forward and backward propagating branches which couple to TM polarized radiation. These branches intersect at the design wavelength, where the surface has a broadside beam with 20° FWHM. The principle branches of the structure show near-unity absorptance. While the physics of the surface are similar in some respects to coherent emission from gratings, the field in the leaky-wave surface is well confined in guided modes bound in the standoff and is not based on diffraction. This makes the surface well suited to sensing applications as well as engineering the radiation heat-transfer properties of the surface.

8806-35, Session 7

Multiplex-bands spectral characteristics of infrared perfect absorber metamaterials

Yongqian Li, Lei Su, Binbin Wang, Yongjun Guo, Jinglong Wang, Northwestern Polytechnical Univ. (China)

Much of the work on the perfect absorber metamaterials focused on overcoming the narrowband limit through multi-resonance or broadband structures. The multiple structure mechanism and the multi-resonant structures have been experimentally demonstrated last decades, by creating unit cells that resonant responses occur at more than one frequency, using lumped resistance elements or exploiting higher order modes of a single resonant structure. These designs utilize single unit cell that resonates at different spatial areas or two structures resonating separately for different frequencies.

There are some furthermore mechanisms to develop such a multiplex resonance research of the metamaterials. In this research, the multiplex absorption metamaterials elements (such as asymmetric cross and metallic rectangle blocks arrays) at mid-infrared realm were investigated through the analysis of their optical parameters and the polarization incident configuration. The orthorhombic polarization configurations play a role of multiplex resonant wavelength contributor as well as a switcher. Similar with the perfect absorber metamaterials, the designed nanostructure consists of metallic cross (or square) structure and a metallic ground plane separated with a dielectric between them, as shown in Fig.1 (a). The strong multiplex resonances at infrared frequency (2µm -10µm) were interpreted through the physical modes and the experimental verification. We experimentally realized that there were multiplex narrow-band infrared absorption peaks in several types of perfect absorber metamaterials, such as that listed in Fig.2. Both the interpretations and the analysis mode of the electromagnetic permittivity and permeability for kinds of the perfect absorber metamaterials have been adopted to explain the consistence of the multiplex resonance wavelength and their optical parameters. Through the performing of the absorption measurements, we try to explain the multiplex-band resonant spectra of the PAMs through our models built, which may directly interpretate other interactions of the nanostructure tailoring the electromagnetic spectrum.

8806-36, Session 7

3D CMOS-compatible plasmonic and metamaterial structures

D. Bruce Burckel, Sandia National Labs. (United States)

Recently we have demonstrated membrane projection lithography (MPL) as a fabrication approach capable of creating 3D structures with sub-micron metallic inclusions for use in metamaterial and plasmonic applications using polymer material systems[1-3]. While polymers provide several advantages in processing, they are soft and subject to stress-induced buckling. Furthermore, in next generation active photonic structures, integration of photonic components with CMOS electronics is desirable. While the MPL process flow is conceptually simple, it requires matrix, membrane and backfill materials with orthogonal processing deposition/removal chemistries. By transitioning the MPL process flow into an entirely inorganic material set based around silicon and standard CMOS-compatible materials, several elements of silicon microelectronics can be integrated into photonic devices at the unit-cell scale. This paper will present detailed fabrication and characterization data of these materials, emphasizing the processing trade space as well as optical characterization of the resulting structures.

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8806-37, Session 7

Negative differential thermal emitter

Mikhail A. Kats, Romain Blanchard, Shuyan Zhang, Patrice Genevet, Changhyun Ko, Shriram Ramanathan, Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

Thermal radiation is light that is spontaneously emitted from an object at a temperature above absolute zero. The spectrum and intensity of thermal radiation are a function of temperature and the emissivity of the object, which is frequency-dependent, as expressed in Planck's law. Integrating over all frequencies the Stefan-Boltzmann law of thermal radiation is obtained, which states that the total energy density emitted is proportional to the fourth power of temperature. This is congruent with every-day experiences that hotter objects emit more light, corresponding to a strictly positive differential thermal emittance.

We show that the differential thermal emittance can become negative in a geometry which exhibits an absorption resonance that can appear and disappear as a function of temperature. Our geometry involves a thin (~150 nm) film of vanadium oxide (VO2), a phase change material, on a sapphire substrate. Recently, we showed that a film of VO2 deposited on sapphire can operate as a temperature-tunable absorber. As absorptivity and thermal emissivity are related, such a structure is expected to have a temperature-dependent emissivity.

We measured the thermal emission from our VO2/sapphire samples over the 8-14 µm window, and observed that in the vicinity of the IMT the sample exhibits a large negative thermal emittance. Imaging with a thermal camera shows that the sample appears cooler even as it is heating up over the 73 – 85 °C range. This phenomenon can find uses in applications such as infrared camouflage and thermal tagging/identification.

8806-38, Session 7

Control near- and far-field thermal radiation with nanophotonic concepts *(Invited Paper)*

Shanhui Fan, Zongfu Yu, Nicholas P. Sergeant, Stanford Univ. (United States); Torbjorn Skauli, Norwegian Defence Research Establishment (Norway); Gang Zhang, Peking Univ. (China); Hailiang Wang, Eden Rephaeli, Aaswath P. Raman, Stanford Univ. (United States)

We present some of our recent works on using nanophotoinc concepts to control thermal radiation. In particular, we show that density-of-state engineering can lead to tremendous enhancement of far-field thermal radiation, far beyond the apparent blackbody limit, without violating the second law of thermodynamics. We also discuss the possibilities for thermal radiative cooling during daytime using nanophotonic design.

8806-39, Session 8

Magnetic light: visible resonant properties of high-refractive index dielectric nanostructures *(Invited Paper)*

Arseniy I. Kuznetsov, Yuan Hsing Fu, A*STAR - Data Storage Institute (Singapore); Andrey E. Miroshnichenko, The Australian National Univ. (Australia); Ye Feng Yu, Mohsen Rahmani, Zhenying Pan, Vytautas Valuckas, Boris S. Luk'yanchuk, A*STAR - Data Storage Institute (Singapore)

High-refractive index dielectric nanoparticles are novel and unique objects in nanophotonics, which can complement or even substitute metallic nanoparticles in the visible spectral range for various applications. According to theoretical predictions based on Mie theory [1] they can have strong resonant responses of both electrical and magnetic nature, which spectral positions are linearly scalable with particle sizes. Recently we have experimentally demonstrated strong magnetic and electric dipole resonances tuneable through the whole visible and near-IR spectral ranges in silicon nanoparticles with sizes ranging from 100 nm to 300 nm [2, 3]. We have also shown that these nanoparticles have unique far-field scattering pattern, which directivity can be controlled changing nanoparticle size and the light wavelength [4]. These optical properties arise due to simultaneous excitation and mutual interference of magnetic and electric dipole resonances inside a single nanosphere. Such behaviour is similar to Kerker's-type scattering by hypothetic magneto-dielectric particles predicted theoretically three decades ago [5]. For nanoparticles with sizes ranging from 100 nm to 200 nm, forward-to-backward scattering ratio above 6 has been experimentally obtained in our work. We will also discuss applications of unique optical properties of high-refractive index dielectric nanoparticle to design of novel low-loss optical nanoantennas and other nanophotonic devices.

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8806-40, Session 8

Magnetic lenses of surface magnetoplasmons in INSB-glass waveguide arrays

Yung-Chiang Lan, Siang-Hao Wu, National Cheng Kung Univ. (Taiwan)

Magnetic lenses are devices to focus or deflect the charged particles by applying magnetic Lorentz force. Since optical beams are uncharged, the magnetic fields are of no effects on them. Recently, focusing lenses for surface plasmons (SPs) in metal-dielectric waveguide arrays (MDWAs) have been proposed and examined. In these MDWAs lenses, a gradient of thickness or refraction index in dielectric material is used to generate the phase difference of SPs in different channels. However, the functions of these lenses are inflexible and cannot be modulated. The dispersion relations of surface magnetoplasmons (SMPs) are manageable by applying external magnetic fields. Hence, it is possible to design devices to steer SMPs by using magnetic fields. In this work, the magnetic lenses for SMPs in InSb-glass waveguide arrays (ISGWAs) under Voigt configuration are proposed and investigated using simulations and theoretical analyses. The FDTD program, VORPAL, is adopted in this study with using the linear plasma dielectric model to represent the magnetized plasmons in InSb layers. The functions of the magnetic lenses of ISGWAs that can focus, deflect, or control the SMP beams are demonstrated. The operation frequency of incident beams is about 1 THz with the largest applied magnetic field of 1 Tesla. The Hamiltonian optics method is utilized to predict and analyze the trajectories of the incident beam. The relations between the focal length and the magnetic field profile in ISGWAs are also elucidated.

8806-41, Session 8

Hyperbolic dispersion of metamagnetics

Vladimir P. Drachev, Univ. of North Texas (United States); David Lyvers, Univ. of North Texas (United States) and UES, Inc. (United States); Dean P. Brown, UES, Inc. (United States); Mark A. Walker, General Dynamics Information Technology (United States); Alexander V. Kildishev, Purdue Univ. (United States); Augustine M. Urbas, Air Force Research Lab. (United States)

In a hyperbolic medium, the principal components of the permittivity have opposite signs causing the medium to exhibit a 'metallic' type of optical response in one direction, and a 'dielectric' in the other resulting in interesting applications. A nanolithography pattern was demonstrated with a hyperbolic slab made of many thin planar layers of a metal and dielectric [1]. Improving the radiative decay rate for dye molecules with hyperbolic metamaterials was shown with a similar multilayer structure by measuring their life time and quantum yield [2].

Here we study hyperbolic dispersion of metamaterials with magnetic response. Recently we explored the group delay dispersion of metamagnetic gratings by the multiphoton intrapulse interference phase scan technique [3], which enables their use for ultrafast pulse shaping. The metamagnetic films have properties of biaxial anisotropic materials. In contrast to uniaxial hyperbolic metamaterials, metamagnetics represent a more general example of indefinite media [4] where both permittivity and permeability components have opposite signs depending on the wavelength. This paper presents our findings on the dispersion of metamagnetic gratings.

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8806-42, Session 8

Metamaterial-enhanced magnetoelectric effects in axionic media

Yong Zeng, Los Alamos National Lab. (United States)

The axionic electromagnetics describes how the presence of a nontrivial background of a putative axion field would modify standard electrodynamics. Recently, it is found that the axionic electromagnetics can be applied to describe low-energy topological insulators, especially the magneto-optical Kerr effect and Faraday effect.

In this talk, I will present a general three-dimensional numerical algorithm which can simulate arbitrary axionic system. I will also show that one can significantly enhance the axionic magnetoelectric effect by using metamaterials.

8806-43, Session 8

Magneto-induced anisotropy of Voigt effect and other magneto-optical phenomena in ordered metal-dielectric metamaterials

Yakov M. Strelniker, Bar-Ilan Univ. (Israel); David J. Bergman, Tel Aviv Univ. (Israel)

It is known that the Voigt, Faraday and other magneto-optical effects can be significantly enhanced in the vicinity of an electromagnetic resonance. One such resonance, which is currently under intensive study, is the surface plasma resonance. It is widely believed that this or similar resonances are responsible for the Extraordinary Light Transmission through a metal film, perforated by a periodic array of sub-wavelength holes, as well for other new phenomena recently found in photonic crystals. Application of a static magnetic field B0 to such systems induces strong optical and transport anisotropy and leads to the appearance of additional off-diagonal tensor components in the effective permittivity tensor and changes the frequency of the surface plasma resonance. Therefore, the application of a static magnetic field to a conducting system with dielectric islands or to a dielectric system with metallic islands should lead to the appearance of strong magneto-optical effects and to possibilities for the manipulation of light propagation.

We have studied analytically and numerically the rotation and ellipticity of polarization of the light propagating through a metamaterial film with periodic microstructure for arbitrary direction of the applied static magnetic field, including both Voigt (when the static magnetic field is in the film plane) and Faraday (when that field is perpendicular to the film) configurations. In the Voigt configuration we found a strong dependence of the above mentioned effects on the direction of the applied field.

8806-44, Session 8

Lattices of magnetoelectric point scatterers in front of an interface

Andrej Kwadrin, A. Femius Koenderink, FOM Institute for Atomic and Molecular Physics (Netherlands)

In the community of metamaterials it is common nature to strive for a simplified description of the artificial medium in terms of effective medium parameters. However, this approach potentially obscures the underlying nature of the material constituents, the meta-‘atoms’. This firstly concerns the electric and magnetic polarizability of each constituent, and secondly any higher order multipolar behavior relevant when studying phenomena involving distances comparable to the metamaterial building block size.

An excellent approach to study these properties is to understand the combined system formed by a metamaterial array and an interface. In our experiment, we collect normal incidence reflectivity and dark field spectra of lattices of split ring resonators (resonant in the near-infrared) for different lattice-interface separations, where the interface is a silver mirror. We compare our data to point dipole lattice sum calculations suitable for arbitrary magnetoelectric point scatterers and find deviations to common approximations such as treating the combined system in a Fabry-Pérot or image dipole model. We attribute this discrepancy to two effects. Firstly, a multilayer model in which each layer is described by its complex amplitude reflection and -transmission coefficients, r and t, cannot describe fields close to the lattice (separations << resonance wavelength). Secondly, the nontrivial local density of states introduced by the interface modifies the radiative damping of each individual scattering element.

8806-45, Session 9

Engineering the coherent, thermal, and quantum state of light using metamaterials *(Invited Paper)*

Zubin Jacob, Univ. of Alberta (Canada)

Nano-Energy: We show that engineering the poles and zeros of the dielectric function using artificial media leads to narrowband, tunable, spatially coherent thermal sources both in the far-field and near-field. We propose the use of high melting point plasmonic building blocks for metamaterials overcoming the critical roadblock for high temperature applications. Our proposed thermal sources can lead to highly efficient thermophotovoltaic energy conversion beyond the Shockley-Queisser limit.

Nano-Quantum: We show that metamaterials can allow control not only over the fields but also the field fluctuations. In particular, we develop the Rytov fluctuational electrodynamics of metamaterials with hyperbolic dispersion to show the enhanced thermal and zero point fluctuations in a prescribed broad bandwidth. One application of this phenomenon is enhancing the spontaneous emission in a broad spectral range for coupling to emitters such as nitrogen vacancy centers in diamond, not possible with cavity approaches.

8806-46, Session 9

Quantum plasmonics *(Invited Paper)*

Andrey K. Sarychev, Institute for Theoretical and Applied Electrodynamics (Russian Federation); Ilya A. Fyodorov, Moscow Institute of Physics and Technology (Russian Federation); Alexei Bogdanov, HGST (United States); Andrey N. Lagarkov, Institute for Theoretical and Applied Electromagnetics (Russian Federation); Gennady Tartakovsky, AS&T (United States)

Surface plasmon nanolasers, also known as SPASERs attract much attention in recent years due to the numerous potential applications in the plasmonics. In this work, we consider the metal horseshoe nanoresonator filled with the active dielectric medium. The size of the considered resonator is much less than the wavelength. On this scale, the plasmon field inside the nanoresonator behaves as a quantum object. The plasmon quantum field is subject of the random external force because of the quantum-mechanical process of the photon absorption in the active medium. Due to the small size of the resonator, the coupling between the plasmon field and an atom of the active medium is anomalous strong. The interaction cannot be considered as just emission or absorption processes. We develop the quantum dynamics of the plasmon field coupled with the active medium. Thus, we consider how the quantum fluctuations influence the process of the luminescence and find how the lasing threshold is changed. The coherence of the light emitted by the plasmon laser is also considered. We predict that the light beams, radiated from non-interacting plasmon nanolasers, could not give the interference pattern. The quantum properties of the nanolaser are important for many applications, such as transmitting and processing optical signals on a scale much smaller than the wavelength.

8806-47, Session 9

RF squid quantum metamaterials *(Invited Paper)*

Melissa Trepanier, Daimeng Zhang, Univ. of Maryland, College Park (United States); Oleg Mukhanov, HYPRES, Inc. (United States); Steven M. Anlage, Univ. of Maryland, College Park (United States)

We are developing active metamaterials capable of quickly tuning their electrical and magnetic responses over a wide frequency range. These metamaterials are based on superconducting elements to form extremely low insertion loss, physically and electrically small, highly tunable structures for the next generation RF electronics. The meta-atoms are RF superconducting quantum interference devices (SQUIDs) that incorporate the Josephson effect. RF SQUIDs are essentially a quantum version of the split-ring resonator in which the inductance now includes a contribution from the Josephson inductance of the junction. This inductance is strongly tunable with DC and RF magnetic fields and currents. We will present experimental and numerical results from the first generation samples, and discuss the degree of tunability of these new meta-atoms. This work is supported by the NSF-GOALI program through grant # ECCS-1158644, and CNAM.

8806-48, Session 9

Nonlocal modification and quantum optical generalization of effective-medium theory for metamaterials *(Invited Paper)*

Martijn Wubs, Wei Yan, Technical Univ. of Denmark (Denmark); Ehsan Amooghorban, Shahrekord Univ. (Iran, Islamic Republic of); Niels A. Mortensen, Technical Univ. of Denmark (Denmark)

A well-known challenge for fabricating metamaterials is to make unit cells significantly smaller than the operating wavelength of light, so one can be sure that effective-medium theories apply. But do they apply? Here we show that nonlocal response in the metal constituents of the metamaterial lead to modified effective parameters for strongly subwavelength unit cells. For infinite hyperbolic metamaterials, nonlocal response gives a very large finite upper bound to the optical density of states that otherwise would diverge [1]. Moreover, for finite hyperbolic metamaterials we show that nonlocal response affects their operation as superlenses, and interestingly that sometimes nonlocal theory predicts the better imaging [2]. Finally, we discuss how to describe metamaterials effectively in quantum optics. Media with loss or gain have associated quantum noise, and the question is whether the effective index is enough to describe this quantum noise effectively. We show that this is true for passive metamaterials, but not for metamaterials where loss is compensated by linear gain. For such loss-compensated metamaterials we present a quantum optical effective medium theory with an effective noise photon distribution as an additional parameter. Interestingly, we find that at the operating frequency, metamaterials with the same effective index but with different amounts of loss compensation can be told apart in quantum optics [3].

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8806-49, Session 10

Dynamics of metamaterials with quantum gain *(Invited Paper)*

Ortwin Hess, Imperial College London (United Kingdom)

Nanoplasmonics and optical metamaterials have in the last 10-15 yeas emerged as a new paradigm in optics and nanoscience, enabling the efficient coupling of light fields to the nanoscale and paving the way for a multitude of classical and quantum nano-optics applications. However, metal optics suffers from inherent dissipative losses and only recently theoretical and experimental advancements have shown that it is realistically possible to overcome dissipative losses of nanoplasmonic metamaterials, even in the exotic negative-index regime [1]. If the gain supplied by the active medium is sufficient to overcome dissipative and radiative losses [2,3], the structure can eve function as a coherent emitter of surface plasmons over the whole ultrathin 2D area, well below the diffraction limit for visible light [4,5]. The talk will give an overview of recent advances in the field of gain-enhanced plasmonics and optical metamaterias and show that these constitute an exciting new frontier in nanophotonics and nanoscience, and are precursors towards active, intergrated quantum nano-optics [6]. Bringing gain to the nanoscale is anticipated to improve the performance of a host of active nano-components, such as electro-optic modulators and light sources, but also passive ones, such as plasmonic waveguides or sensors featuring intensified plasmonic hotspots for single-emitter spectroscopy.

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8806-50, Session 10

Engineered metals for mid-IR plasmonics

Stephanie Law, Univ. of Illinois at Urbana-Champaign (United States); Christopher Roberts, Univ. of Massachusetts Lowell (United States); Jonathan R. Felts, Torin Kilpatrick, William P. King, Univ. of Illinois at Urbana-Champaign (United States); Viktor A. Podolskiy, Univ. of Massachusetts Lowell (United States); Daniel M. Wasserman, Univ. of Illinois at Urbana-Champaign (United States)

The ability to strongly confine incident mid-IR light to subwavelength geometries has the potential for significant impact in molecular sensing, thermal signature control, and IR optoelectronics applications. While plasmonics has been hailed as a route to subwavelength photonic systems at short wavelengths, the properties of metals at longer wavelengths results in very different optical behavior of plasmonic structures at these longer wavelengths, especially in the near-field. However, by replacing traditional plasmonic metals such as Ag and Au with engineered metals consisting of highly-doped semiconductor materials, strong confinement of mid-IR light becomes possible.

Plasmonic structures are fabricated using our heavily-doped semiconductor materials, in order to demonstrate subwavelength confinement and control of mid-IR light with engineered mid-IR plasmonic metals. First, micro-structures from single-layer doped InAs films are fabricated, and these structures' ability to support localized surface plasmon resonances in the mid-IR is demonstrated. The micro-particles are characterized by both near-field and far-field spectroscopic techniques and simulated by finite element methods. In addition, all-semiconductor plasmonic absorbers are fabricated from multilayer first growth samples and absorption of >98% observed at resonance, largely independent of our structure's lateral geometry. Our perfect absorbers are characterized by infrared microscopy and simulated using finite

difference time domain (FDTD) techniques and rigorous coupled wave analysis (RCWA).

In summary, we demonstrate the potential of engineered plasmonic metals for strong localization of long wavelength light. The ability to strongly confine mid-IR light to subwavelength geometries has the potential for integration into a new generation of sensing, thermal signature control, and optoelectronic structures and devices.

8806-51, Session 10

All-dielectric metamaterials: path to low losses and high spectral selectivity *(Invited Paper)*

Gennady B. Shvets, Nihal Arju, Institute for Fusion Studies (United States); Michael B. Sinclair, Igal Brener, Sandia National Labs. (United States)

Ohmic losses severely limit the performance of metamaterials. High-index semiconductors offer an attractive alternative. We review several meta-surfaces based on silicon and silicon carbide enabling infrared applications such as polarization manipulation and thermal emission. Non-metallic (dielectric or semiconductor) metamaterials present a unique opportunity for developing electromagnetically complex multi-resonant meta-surfaces while avoiding Ohmic losses. For example, Fano-resonant structures exhibiting sharp resonances caused by the interference between sub-radiant and super-radiant resonances can be designed and utilized for highly spectrally selective thermal emissivity, polarization manipulation, nonlinear optics, and full Stokes parameter hyper-spectral polarimetry.

I will also report the results of theory, design, fabrication, and optical characterization of large-area meta-surfaces (MSs) for thermal emission comprised of SiC antennas shown in Fig.2. The attraction of semiconductor-based thermal emitters is three-fold. First, optical properties of many semiconductors are essentially frequency-independent across broad spectral range, unlike those of plasmonic structures. Second, the ability to affect the refractive index of semiconductors by introducing free carriers enables either active or passive control of their optical properties. Third, high conductivity of doped semiconductors enables their electric heating.

8806-52, Session 10

Direct fs laser writing: principles and applications *(Invited Paper)*

Elmina Kabouraki, Ioanna Sakellari, Maria Vamvakaki, David Gray, Maria Farsari, Foundation for Research and Technology-Hellas (Greece)

We present a new method for increasing the resolution of direct fs laser writing by multiphoton polymerization, based on quencher diffusion. This method relies on the combination of a mobile quenching molecule with a slow laser scanning speed, allowing the diffusion of the quencher in the scanned area and the depletion of the multi-photon generated radicals. We use this method to fabricate dielectric, metallic and quantum-dot doped photonic crystals and we show that the results are comparable to those produced by direct laser writing based on stimulated-emission-depletion microscopy, the method considered today as state-of-the-art in 3D structure fabrication. We model the quencher diffusion and we show that radical inhibition is responsible for the increased resolution. Finally, we discuss applications of Direct fs Laser Writing in photonics, metamaterials, and biomedical Implants.

8806-53, Session 10

Bichromatic wave mixing to reach optically lossless semiconductors

Adil-Gerai Kussow, Yassine Ait El Aoud, Alkim Akyurtlu, Univ. of Massachusetts Lowell (United States)

Two-wave mixing in non-ohmic semiconductors with low dispersion to dramatically reduce optical losses is proposed. The optical losses in the probe mode are fully compensated due to the flow of energy from the support mode. The total-loss-suppression effect is derived from the solution of non-linear Maxwell equations combined with coherence conditions for two parametrically coupled waves. We provide a scenario which demonstrates that this scheme can be realized experimentally in bulk semiconductors, e.g. zinc telluride (ZnTe), within the mid-IR regime, and preliminary experimental results are discussed.

8806-54, Session 10

Low index metamaterials comprised of plasmonic dimers of aluminum doped zinc oxide

Hossein Alisafaee, Princess M. Cox, Michael A. Fiddy, The Univ. of North Carolina at Charlotte (United States)

The behavior of localized surface plasmon resonances (LSPR) of AZO nanoparticle dimers embedded in a host polymer medium is investigated for different dimer orientations with respect to the indicent electromagnetic wave. In doing this, the role of dressed polarizability to enhance and quench the plasmonic effects is also considered. The effects of the nanoparticles' relative size and the spacing between them are studied. The frequency of LSPR is found in the near infrared (NIR) spectral region. Understanding these resonances and their dependence on dimer orientations, provides a means to design metamaterial structures for use in the NIR region with epsilon-near-zero properties leading also to low index metamaterials. In our studies, we demonstrate how nanospheres with radii less than 100 nm that are distributed with an average spacing less than their diameter, can result in an effective medium with refractive index less than one. Since our study is in the NIR, where the resonant behavior of AZO nanoparticles is dominant, simple effective medium models such as Bruggeman's cannot be applied while the high particle density also prevents us from employing a Maxwell-Garnet model. Consequently, we utilize a full-wave frequency domain finite element method in conjunction with an equivalent-circuit model for the nanoscale dimers in order to describe the spectral response of the bulk low index properties. We also present a statistical analysis to obtain the effective refractive index for incident light having different polarizations. The results from our model are compared with those of the Bruggeman and Maxwell-Garnet effective medium approximations.

8806-55, Session 11

Tuning plasmon resonances by electrochemical potential control *(Invited Paper)*

Harry A. Atwater Jr., California Institute of Technology (United States)

Recently considerable attention has turned towards the relationship between plasmon excitation and the electrochemical potential associated with the electron gas in a conductor. In this paper, we explore this relationship in three contexts: 1) the plasmoelectric effect, a new physical phenomenon that relates resonant excitations in conductors to their electrochemical potentials and 2) field effect tuning of the electrochemical potential and plasmon resonances of graphene nanoresonators and 3) transport of plasmon-excited hot carriers across metal-semiconductor interfaces.

The plasmoelectric potential is an electrochemical potential induced by resonant optical absorption in plasmonic nanostructures. This electrochemical potential results from the dependence of the plasmon resonance frequency on electron density. We demonstrate experimentally the relationship between plasmoelectric potential and resonant optical absorption via three independent experimental methods: 1) electrochemical potential measurements made by Kelvin probe force microscopy observations of Au nanoparticles on conducting substrates 2) potential measurements between two photoelectrochemical cells connected by a salt bridge and 3) comparison of extinction spectra take under broadband 'white' illumination and scanned monochromatic excitation.

We report the gate-tunable resonant absorption in lithographically fabricated arrays of graphene ribbon plasmonic nanoresonators with cavity lengths in the 10-100 nm range. Resonant mid-infrared absorption features due to transverse and longitudinal plasmonic cavity resonances are observable, as are plasmonic features that couple to localized phonon modes in the underlying silicon dioxide substrate. The plasmonic dispersion relations for these resonators can be developed by variation of resonant energy with cavity length as a function of gate voltage. The relationship between cavity edge roughness and resonance linewidth will be discussed.

Recently considerable attention has turned towards finding a silver lining in the cloud of plasmonics by extracting energy from the inevitable optical losses resulting from plasmon decay. We assess the prospects energy conversion via hot electron injection from localized plasmon decay across a rectifying metal-semiconductor Schottky barrier junction. Of particular interest is the relationship between the injection current across the Schottky barrier and the polarization of the electric field used to excite the plasmon. We analyze the current injection in Au/Si Schottky barrier nanoantennas excited with fields polarized transverse and parallel to the heterojunction interface.

8806-56, Session 11

On the calculation of optical force and stress in metamaterials *(Invited Paper)*

Che-Ting Chan, Hong Kong Univ. of Science and Technology (Hong Kong, China)

We will talk about some calculations we have done on the light induced force and stress. We show that some special non-diffracting beams can attract particles with simultaneous electric and magnetic responses. For dielectric particles, such attractive forces happen in the Mie regime. For metamaterial particles with both electric and magnetic resonances, it is possible to attract particles even in the Rayleigh regime. In addition, we would like to show that attractive light forces that are strong in magnitude with a reasonable power of the incident light can be achieved. One possible configuration is to use a near field approach and employ the evanescent field of a plasmonic excitation. For example, we can use light to excite the plasmonic resonance of a configuration that is the counterpart of high-impedance "meta"-surfaces. We will discuss experimental effort in this area. We will also address the question of electromagnetic induced stress inside a metamaterial. This is a difficult problem both technically and conceptually, as it is not easy to distinguish between the material and the field part of the momentum density. We find that the usual effective permittivity and permeability parameters do not give sufficient information to determine the force density inside a metamaterial if the field penetrates the material and we show that the required additional parameters can be calculated semi-analytically using a multiple scattering formalism.

8806-57, Session 11

Modeling and understanding of effects of randomness in arrays of resonant meta-atoms *(Invited Paper)*

Sergei Tretyakov, Mohammad Albooyeh, Pekka Alitalo, Aalto Univ. School of Science and Technology (Finland); Andrei Andryieuski, Technical Univ. of Denmark (Denmark); Ali Culhaoglu, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Andrei V. Lavrinenko, Technical Univ. of Denmark (Denmark); Dmitry Morits, Aalto Univ. School of Science and Technology (Finland); Constantin Simovski, Aalto Univ. School of Electrical Engineering (Finland)

In this review presentation we will discuss approaches to modeling and understanding electromagnetic properties of 2D and 3D lattices of small resonant particles (meta-atoms) in transition from regular (periodic) to random (amorphous) states.

Nanostructured metasurfaces (2D) and metamaterials (3D) are arrangements of optically small but resonant particles (meta-atoms). The main focus of research of these structures has been on the case of periodical arrays of meta-atoms. However, most recently, random or amorphous metamaterials start to attract attention, due to novel technological possibilities to manufacture amorphous structures cheaply and on a large scale, and there is a need to develop predictive analytical tools for the design of amorphous metamaterials. We will present our results on analytical modeling of metasurfaces with periodical and random arrangements of electrically and magnetically resonant meta-atoms with identical or random sizes, both for the normal and oblique-angle excitations. We show how the electromagnetic response of metasurfaces is related to the statistical parameters of the structure.

Effective parameters of many metamaterials exhibit a so called anti-resonance, which is a nonphysical feature, in at least one of the parameters that are retrieved this way. Many previous works have either claimed or assumed that the anti-resonance is an effect caused by the periodicity of the composite material. Here we will discuss the question if the sample periodicity is indeed essential for appearance of anti-resonances in extracted material parameters. Our conclusion, supported by both numerical simulations and microwave experiments, is that both periodic and random arrays clearly show similar anti-resonance of the extracted material parameters. It means that the physical reason of the anti-resonant behavior of effective parameters is the resonant response of finite-size inclusions and unit cells, while the particular arrangement of these cells is not essential.

8806-58, Session 11

Trapping light by mimicking gravitational lensing

Hui Liu, Chong Sheng, Yi Wang, Shining Zhu, Nanjing Univ. (China); Dentcho A. Genov, Louisiana Tech Univ. (United States)

Recently, there is an increasing interest in light trapping in microstructures. Furthermore, it has been suggested that artificial optical materials and micro-structured waveguides may be used to mimick celestial phenomena such as light trapping in gravitational black holes, Hawking's radiation etc.. In astronomy, gravitational lensing, which was theoretically proposed by Albert Einstein, has become an important tool to map large scale structures such as gas clouds, dark matter halos in the galaxy and others. However, the stronger lensing effects in close proximity to ultra-compact objects such as black holes and neutron starts have not yet been observed.

In this paper, we propose a distorted waveguide around microsphere that mimics the gravitational lensing effects in close proximity to such compact objects and specifically those with asymptotic polytropic equation of state. Our methodology can be used to experimentally study, for a first time, strong gravitational effects such as light capture and existence of photon spheres around these objects. Other possible applications may be in energy harvesting devices due to the omnidirectional absorption properties of our system as well as for applications as high Q-factor optical cavities.

8806-59, Session 11

Experimental demonstration of metamaterial multiverse in a ferrofluid *(Invited Paper)*

Igor I. Smolyaninov, Univ. of Maryland (United States); Bradley Yost, Evan Bates, Vera N. Smolyaninova, Towson Univ. (United States)

Extraordinary light rays propagating inside a hyperbolic metamaterial look similar to particle world lines in a 2+1 dimensional Minkowski spacetime. Magnetic nanoparticles in a ferrofluid are known to form nanocolumns aligned along the magnetic field, so that a hyperbolic metamaterial may be formed at large enough nanoparticle concentration nH. Here we investigate optical properties of such a metamaterial just below nH. While on average such a metamaterial is elliptical, thermal fluctuations of nanoparticle concentration lead to transient formation of hyperbolic regions (3D Minkowski spacetimes) inside this metamaterial. Thus, thermal fluctuations in a ferrofluid look similar to creation and disappearance of individual Minkowski spacetimes (universes) in the cosmological multiverse. This theoretical picture is supported by experimental measurements of polarization-dependent optical transmission of a cobalt based ferrofluid at 1500 nm.

8806-60, Session 11

Solids in ultrafast and strong optical fields: new phenomena *(Invited Paper)*

Mark I. Stockman, Georgia State Univ. (United States)

We report theory and experimental results for a new class of phenomena in condensed matter optics when strong optical fields ?0.1-3 V/Å reversibly change the solid within an optical period [1-5]. Such fields, if adiabatic, cause phenomena such as the Wannier-Stark localization and anticrossings of adiabatic levels. During a single-oscillation strong optical pulse, a dielectric undergoes a reversible transition to a semi-metal, which follows the instantaneous optical field during time intervals on order of hundred attoseconds. Such a pulse drives currents in dielectrics and controls their properties, including optical absorption and reflection, and extreme UV absorption in a non-perturbative manner. Applied to a metal, such a pulse causes an instantaneous and reversible loss of the metallic properties. These are fastest phenomena in optics and offer potential for petahertz-bandwidth signal processing.

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8806-61, Session 11

Plasmonic resonances, enhanced optical properties, and other optical phenomena in novel eutectic and nanoparticles-based composites *(Invited Paper)*

Dorota A. Pawlak, Marcin Gajc, Katarzyna Sadecka, Pawel Osewski, Andrzej Stefanski, Sebastian Turczynski, Andrzej Klos, Barbara Surma, Institute of Electronic Materials Technology (Poland)

Developments of the materials for plasmonics and metamaterials by two novel bottom-up manufacturing methods will be presented. These methods are based on: (i) directional solidification of eutectic composites and (ii) NanoParticles Direct Doping (NPDD) - doping dielectric matrices with plasmonic nanoparticles. In both cases we apply one of the crystal growth methods - the micro-pulling down method - to create the material. Materials with plasmonic resonances at visible and IR wavelengths will be presented, as well as their influence on photoluminescence or nonlinear properties of the materials. Our new approach may lead to novel manufacturing solutions for photonic applications.

8806-62, Session 12

THz metamaterial effects in phonon-polariton composite media *(Invited Paper)*

Maria Kafesaki, Foundation for Research and Technology-Hellas (Greece) and Univ. of Crete (Greece); Alexey Basharin, Charalambos Mavidis, Eleftherios N. Economou, Foundation for Research and Technology-Hellas (Greece); Costas M. Soukoulis, Foundation for Research and Technology-Hellas (Greece) and Iowa State Univ. (United States)

Polaritonic materials (i.e. materials showing phonon polariton modes) are becoming recently a more and more valuable component of THz metamaterials. This is due to the resonant permittivity response that they exhibit in the THz regime, involving a wide range of permittivity values, from high positive to near-zero and negative ones. Thus, polaritonic materials give the possibility, if properly structured, to obtain a rich variety of metamaterial related phenomena and capabilities. In this talk we will discuss polaritonic systems made of rods periodically placed in a host and we will describe the rich phenomena and capabilities that such systems can offer. These phenomena include negative permittivity, negative permeability and negative index response, indefinite media response leading to subwavelength resolution imaging capability (hyperlensing), backwards radiation leading also to subwavelength propagation, total transmission or reflection due to the excitation of Mie-resonant modes of the rods if the host permittivity gets epsilon-near-zero values, as well as sub-wavelength guiding based on such modes. The model systems that we will employ to demonstrate the above mentioned phenomena are systems of LiF rods in NaCl or KCl host. Besides the rich phenomena that can be observed in those systems, another great advantage of them is their easy realization possibility, through eutectics self-organization structuring.

8806-63, Session 12

Modeling and fabrication of Terahertz metamaterials

Mayer A. Landau, U.S. Air Force Research Lab. (United States)

Metamaterials are synthetic materials with periodic electromagnetic inclusions. The interactions between inclusions can fundamentally alter the macroscopic response of the material to electromagnetic radiation. Simulating this response is costly in computer resources due to the sheer number of cell elements involved in a 3D material. It would be ideal to have macroscopic constituitive parameters that capture the essense of the material's response, as index of refraction and impedance do for natural materials. But metamaterials are highly dispersive and their lattice constant is on the cusp of being too large to model effectively with macroscopic constituitive paramaters. Recently (2010) Andrea Alu at UT Austin derived a new metamaterial homogenization theory of macroscopic material parameters (permittivity and permeability) that are dispersion independent. We use these dispersion independent parameters to simulate scattering from finite slabs. These results are compared to FDTD simulations. We also compare to actual experiments with metamaterial filters, i.e. slabs, built to operate at W band and at 1THz. We find the Alu constituitive parameters give good agreement with experiment and provide much faster scattering calculation compared to standard FDTD.

8806-64, Session 12

Modified bow-tie antenna with strong broadband field enhancement for RF photonic applications

Shiyi Wang, Qiwen Zhan, Univ. of Dayton (United States)

We present a novel design of a subwavelength modified bow-tie antenna that is capable of generating strong broadband field enhancement in its extended feed gap. This modified bow-tie antenna is comprised of a conventional bow-tie antenna with capacitive extended bars attached to the apex points of bow-tie. The feed gap between the two capacitive bars is separated with a deep subwavelength width for the generation of enhanced local electrical field. Three-dimensional finite element method model is utilized to systematically explore the properties of this antenna design. Through adjusting the bow-tie geometry and the substrate properties, the antenna structure is optimized with a central resonant frequency at 100 GHz. Highly enhanced electrical field is created between the extended bar under radio frequency (RF) illumination. With the optimized design, numerical simulations show that a uniform field enhancement of more than 200 through the entire feed gap with a bandwidth of 40 GHz can be achieved. The strongly enhanced RF field within the gap can be applied to directly modulate guided optical wave propagating in a waveguide embedded in the substrate underneath the feed gap. This work builds up a bridge between devices in the RF and optical frequency regimes that may find many potential applications in RF photonic devices and systems.

8806-65, Session 12

Polarization properties of 2D and 1D metamaterial lenses

Duncan A. McGillivray, Univ. of Virginia (United States); Robin L. Cravey, Kenneth L. Dudley, Erik Vedeler, NASA Langley Research Ctr. (United States); Mool C. Gupta, Univ. of Virginia (United States)

The unique properties of metamaterials present an opportunity for many novel sensor applications and nondestructive evaluation devices. The polarization properties of metamaterials have not been significantly investigated, in particular in the context of sensors and nondestructive evaluation. This study examines the polarization properties of a split ring resonator and rod (SRR+R) metamaterial array.

The array is configured into a 2-D metamaterial lens and the results are compared to 1-D lens configurations. The polarization properties of the lens configurations were investigated through experiment and FDTD modeling.

It was found that, at resonance frequency of 3.63 GHz, the transmission response of SRR+R metamaterial structures is highly sensitive to the polarization state of the incident microwave. This sensitivity is due to the coupling mechanisms between the incident radiation and the metamaterials constituent elements. For transverse-electric (TE) incident polarization, the 2-D lens alters the polarization state of the incident radiation into elliptical polarization with a tilt along the principal axis, where the ellipticity changes with incident polarization angle. Transverse-magnetic (TM) incident polarization is unaffected by the 2-D metamaterial lens.

The 1-D lens does not affect the polarization of the incident microwave radiation. However, drastic changes in the transmission profile and effective index of refraction were found. These changes are due to the incident polarization state (TE and TM) coupling with the metamaterials constituent elements.

The control over the polarization state of the incident microwave radiation allows to tailor the transmission, which can be leveraged towards novel transmission based microwave metamaterial sensors.

8806-66, Session 12

Filament-based virtual hyperbolic metamaterials for microwave guiding

Zhaxylyk A. Kudyshev, Natalia M. Litchinitser, Univ. at Buffalo (United States)

One of the major challenges in transmitting microwaves in air is that as any electromagnetic beams they diffract. Therefore, in order to be able to receive the signal at a certain distance, one has to counteract this diffraction broadening. In the last few years various types of filament-based waveguides were proposed for channeling microwaves [1-3]. Filamentation of an intense laser pulse is a phenomenon originating from self-focusing. Guiding of microwaves with filaments over 16 cm was experimentally demonstrated by Chateauneuf using a 100 TW laser system to produce a cylindrical array of filaments 45mm in diameter [4]. The detected signal was increased by a factor of ~ 6 compared to the free propagation case.

We propose ordered filament-based photonic structures to reduce microwave beam divergence and route beams around the obstacles. In particular, we design and optimize virtual hyperbolic metamaterials formed from filaments in air. One possible realization of hyperbolic metamaterials is a set of wires with negative dielectric constant in a background medium with a positive dielectric constant [4]. These wires are formed by multiple filaments with a fix fill-fraction of filaments and air. Our proof-of-concept results confirm that microwave beam divergence can be controlled using the proposed metamaterial structure.

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8806-67, Session 13

Advanced solitonic metamaterial waveguide structures under external magnetophotonic control and peregrine creation *(Keynote Presentation)*

Allan D. Boardman, Peter Egan, Univ. of Salford (United Kingdom)

Metamaterial research is an extremely important global activity that promises to change our lives in many different ways, including making objects invisible and having a very dramatic impact upon the energy and medical sectors of society. Behind all of the applications, however, lies the design of metamaterials but this can be led by elegant routes that include nonlinearity, and waveguide complexity, associated with optical device formats and coupling to soliton behaviour. A range of devices will be considered here but a particular interest will be in the use of solitonic Y-junction waveguides and soliton beam and pulse interactions. It will be shown that particular metamaterial environments will completely change everything and open up a dramatic influence on the kind of nonlinear superposition of spatial solitons needed for this application. The implications for planar waveguide sensors are immense and some will be discussed in detail to show how loading, or interacting, them with certain types of metamaterial will lead to measurement outcomes with considerably enhanced sensitivities. All of these discussions will focus upon the need for special metamaterials, or combinations of them, many of which will be hyperbolic and some of which will use interacting metaatoms and magnetoinductive waves. The control of a solitonic metamaterial waveguides through external influences, like magnetooptics, under the general heading of magnetophotonics will also be investigated. In addition, vortex formation will be critically assessed with a view to using metamaterials to enhance the addition of angular momentum to special light beams. In the final section of the presentation, the absolutely fascinating possibility of generating Peregrine solitons, involving localization in both space and time, will be addressed. These solitons are named after Professor Peregrine but also have the same name as the well-known high-speed falcon. This type of soliton is like the rogue hydrodynamic wave that causes so much global damage. It has only recently been observed optically and it will be shown here that the introduction of metamaterials opens up a vast spectrum of opportunities so that the soliton can be used in either a positive, or a negative, way with much more flexibility.

8806-68, Session 13

Graded-index metamaterials: from linear to low-intensity nonlinear optics *(Invited Paper)*

Natalia M. Litchinitser, Zhaxylyk A. Kudyshev, Fatema Alali, Univ. at Buffalo (United States); Ildar R. Gabitov, The Univ. of Arizona (United States); Andrei I. Maimistov, Moscow Institute of Physics and Technology (Russian Federation)

We discuss recent progress in the field of linear and nonlinear light propagation in transition metamaterials, a class of artificial graded-index materials with dielectric permittivity and magnetic permeability gradually changing between positive, zero and negative values. Our initial studies predicted strongly polarization sensitive anomalous field enhancement near the zero refractive index point under oblique incidence of the plane wave on a realistic, lossy transition metamaterial layer, potentially enabling a variety of applications in microwave, terahertz, and optical metamaterials, including subwavelength transmission and low-intensity nonlinear optical devices. In this talk, we compare the phenomenon of resonant field enhancement in the cases of planes wave, Gaussian and Hermite-Gaussian beam propagation in transition metamaterials and demonstrate that in the case of Gaussian beam resonant enhancement occurs for both normal and oblique incidence due to the fact that the beam is composed of a combination of plane waves, each with a different angular vector. We investigated various graded-index structures and predicted a possibility of field enhancement in both positive-zero-negative index structures and positive-zero-positive index profile case. Moreover, we demonstrate that more complex refractive index distributions with, for example, two zero-index crossings, may result in a formation of tunable resonant cavities. Finally, we report our first studies of the effect of resonant enhancement in the transition layer with quadratic nonlinearity enabling enhanced efficiency of second harmonic generation and providing a promising route to low input power nonlinear optical devices.

8806-69, Session 13

Plasmonic enhancement of third order nonlinearity: practical limitations *(Invited Paper)*

Jacob B. Khurgin, Johns Hopkins Univ. (United States); Greg Sun, Univ. of Massachusetts Boston (United States)

Plasmonic structures and metamaterials allow very high degree of concentration of electro-magnetic fields in the vicinity of metal nanoparticles. This effect is known to enhance optical nonlinearities and thus has been suggested as the basis for all optical switching, frequency conversion and other applications. At the same time, being a strongly resonant phenomena, plasmonic enhancement is always impeded by losses in the metal. We show that indeed the effective third order nonlinearity in plasmonic nanostructures can be increased by as much as 5-6 orders of magnitude, but only for weak pumps and signals. This makes nonlinear nanoplasmonics an excellent platform for sensing applications. At the same time, the more relevant figure of merit, the maximum total phase shift attainable in the device cannot exceed a few percent, thus rendering all optical switching and frequency conversion in nanoplasmonic structures extremely inefficient.

8806-70, Session 13

Quantum mechanical modeling of nonlinear surface plasmon polaritons

Fan Wang, Dafei Jin, Nicholas X. Fang, Massachusetts Institute of Technology (United States)

Surface plasmon polaritons (SPP) are coupled collective excitations of electrons and photons at the metal-insulator interface. When the characteristic size of interest shrinks to the order of one nanometer (for example, around a sharp metal tip or across a thin dielectric spacer), the classical treatment will break down; the quantum nature of electrons, such as the tunneling through potential barrier and the interference around structural defect, start to take place. When the deposited energy is sufficiently high, the nonlinear phenomena due to SPP-SPP collision will show up as well. In this work, we adopt coupled nonlinear Schrodinger equation and Maxwell's equations to study the behavior of SPPs in the extreme-quantum and high-energy regime. We calculate the excitation spectrum under various geometric and electrostatic configurations, and investigate the evolution and interaction of SPP vortices in real time. Our work can give a good insight into the underlying physics of this system and may be helpful for designing sub-nanometer plasmonic devices.

8806-71, Session 14

Active metamaterials based on strong coupling to semiconductor excitations *(Invited Paper)*

Igal Brener, Sandia National Labs. (United States)

Planar metamaterials (MM) offer many desirable properties for modulation, filtering and control of the emission of light. The optical response of metallic metamaterial resonators is very scalable through most of the infrared spectrum. Strong coupling between these resonators and optical excitations in semiconductors offers a viable path for tunable and nonlinear optical response.

First, I will present recent results on the strong coupling between metamaterials and intersubband transitions (IST) in semiconductor quantum wells. We can maximize this interaction by proper design of the MM resonators and the semiconductor heterostructure. Our designs lead to a Rabi splitting that can reach 15-20% of the fundamental frequency. Furthermore, this coupling occurs in a deep subwavelength volume. Then, I will describe the strong coupling between MM resonators and epsilon near zero (ENZ) waves present in thin highly doped semiconductor layers. Finally, I will discuss the control of this strong coupling using an external bias.

This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

8806-72, Session 14

Optical switching with phase-change metamaterials *(Invited Paper)*

Kevin F. MacDonald, Jianfa Zhang, Behrad Gholipour, Jonathan S. Maddock, Daniel W. Hewak, Univ. of Southampton (United Kingdom); Nikolay I. Zheludev, Univ. of Southampton (United Kingdom) and Nanyang Technological Univ. (Singapore)

The next phase of the photonic technological revolution will be driven by switchable and nonlinear metamaterials, with properties surpassing those of natural media, as a functional platform for nanoscale 'meta-devices'. We report here on recent advances in the development of versatile, planar photonic metamaterial solutions to provide a new generation of all-optical switching and memory devices.

8806-73, Session 14

Reconfigurable gradient index using VO2 memory metasurface

Michael D. Goldflam, Univ. of California, San Diego (United States); Tom Driscoll, Duke Univ. (United States) and Intellectual Ventures (United States); Daniel Barnas, Omar Khatib, Univ. of California, San Diego (United States); Matthew Royal, Nan M. Jokerst, David R. Smith, Duke Univ. (United States); Bong-Jun Kim, Electronics and Telecommunications Research Institute (Korea, Republic of); Giwan Seo, Univ. of Science & Technology (Korea, Republic of); Hyun Tak Kim, Electronics and Telecommunications Research Institute (Korea, Republic of) and Univ. of Science & Technology (Korea, Republic of); Dimitri N. Basov, Univ. of California, San Diego (United States)

We have demonstrated the creation of spatial gradients in the optical properties of a metamaterial device through tuning of a hybrid metamaterial. Such metamaterials are formed through the combination of tunable substrates with standard metamaterial structures. Our device consists of a vanadium dioxide (VO2) layer that interacts with an array of lithographically fabricated split ring resonators. Application of a transient electrical pulse across the metamaterial-VO2 system leaves persistent changes in the properties of the metamaterial due to the hysteresis of the insulator-to-metal transition in VO2. We demonstrate that through modification of the spatial and temporal distribution of current, we can obtain increased control over the shape of gradients in these devices. Spatial control is achieved through geometrical design of contacts fabricated on the device. Using these methods, we are able to write spatially sharp gradients with ~50 percent change in the index of refraction over length scales of only a few wavelengths as observed through diffraction limited terahertz spectroscopy. Furthermore, we assess the potentials for applications of such gradients in beam-steering.

8806-88, Session 14

Smart metamaterial based on elastic crystals

Dongheok Shin, Yonsei Univ. (Korea, Republic of); Yaroslav A. Urzhumov, Duke Univ. (United States); Youngjean Jung, Kyoungsik Kim, Yonsei Univ. (Korea, Republic of); David R. Smith, Duke Univ. (United States)

We introduce a theory of a smart metamaterial that obtains own electromagnetic properties automatically from given mechanical deformations. Based on transformation optics and solid mechanics, we found the connection between electromagnetic and elastic properties that makes our elastic crystal sample to perform as smart metamaterial. With this concept, we build and experimentally test a transformation optics device - "carpet cloak" – whose functionality derives from quasi-conformal coordinate transformations. The smart metamaterial cloak self-assembles these transformations automatically from an essentially arbitrary deformation of the cloak boundary, eliminating the need to manufacture a large variety of metamaterial unit cells.

8806-84, Session PWed

Modeling of carpet cloak with angle dependent constitutive parameters for terahertz frequency band

Egor A. Gurvitz, Mikhail K. Khodzitsky, Anna V. Vozianova, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Today, metamaterials (structures with unusual properties) become widely known hot topic of applied science [1]. Using metamaterials it can develop new types of waveguide structures, filters, detectors, super resolution imaging devices, antennas, etc. One of the most popular and exotic application of metamaterials is design of cloaking devices to hide objects. In the most cases, transformation optics was used to control of light and hiding of an object [2]. The invisibility effect is achieved by using special spatial distribution of constitutive parameters of cloak which acts as transformation medium. There are three main types of transformation optics cloaks such as spherical, cylindrical and carpet designs[2-4]. The most practicable design is carpet which allows e.g. to hide an object from security systems in terahertz frequency range. Our work is devoted to investigation of THz radiation control using carpet cloak with angle dependent constitutive parameters. The metric tensors of constitutive parameters were obtained for such design. The invisibility effect in such structure was verified by numerical simulation using COMSOL Multiphysics software [5].

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8806-85, Session PWed

Achieving multifrequency cloaking with a single shell of multiple plasmonic constituents

Youwen Liu, Yunji Meng, Nanjing Univ. of Aeronautics and Astronautics (China)

Researches on metamaterial cloaking become very active because of exciting potential applications in various scientific fields. The scattering cancellation cloaking, which exploits negative or low-positive permittivity of homogeneous and isotropic plasmonic layers to cancel the scattering of an object, can be more easily extended to multifrequency operation. As successfully shown, increasing the number of plasmonic layers that provides extra degrees of freedom in the design of the cloak would allow the possibility of drastic scattering reduction simultaneously at multiple frequencies. In this contribution, we proposed a single cloaking shell with different plasmonic composites, which possesses required permittivity properties to reduce the scattering of a given object at multiple frequencies. The results based on the Mie theory, which is verified with numerical simulation, show that extra degrees of freedom for MF cloaking

can be also provided by simply increasing the number of plasmonic constitutes of the thin shell without changing its total thickness. A special design has also been proposed, showing its great feasibility in the practical application.

8806-86, Session PWed

Band-gap structure for n-fold layers inside bilayer cell of photonic crystal for THz frequencies

Alaudi K. Denisultanov, Sergey A. Ozerov, Mihail K. Khodzitsky, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Recent years photonic crystals are very promising and attractive structures for control and manipulation of electromagnetic waves. They can find applications as filters, waveguides, polarization changers, superlenses, superprisms, etc [1]. In particular, photonic crystals are of very interest for terahertz applications as THz components for THz spectroscopy and tomography of biological objects [2]. However for qualitative THz components design there is an actual problem of exact definition of frequency position of center and edges of N-stopband of photonic crystal [3]. So this paper is devoted to theoretical and experimental investigation of band-gap structure for N-fold layers inside bilayer cell of one-periodical (1D) photonic crystal. The band-gap analysis was carried out using the transfer matrix method [4] and CST Microwave Studio software [5]. The formulas for calculation of exact frequency position of centers, edges and width of N-stopband were obtained for four values of multiplicity of layers inside of PC bilayer cell. The verification of these formulas was shown in the experiment in the frequency range from 0.1 to 1 THz.

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8806-87, Session PWed

A dual-band pass filter based on a Zeonor substrate in the THz regime

Jeong Min Woo, Min-Sik Kim, Jae-Hyung Jang, Gwangju Institute of Science and Technology (Korea, Republic of)

There is a growing need for research to control EM waves in the THz regime as such work offers great potential in the bio-medical, agriculture, and chemical fields. The characteristics of metamaterials (MMs) have fulfilled these needs, showing good performance as a frequency selector within a modulator, absorber, and filter. In this study, a dual-band pass filter based on a Zeonor substrate (23 ?) in the THz regime is studied. The transmittance level of the Zeonor substrate was 0.83~0.99 and the refractive index was 1.6 at 1 THz. Due to its good characteristics as a filter substrate, the dual-band pass filter designed here was demonstrated on it. Meanwhile, the metal-deposition step to demonstrate MMs on a Zeonor substrate failed, showing weak adhesion between the metal (Ti/Au=20/200 nm) and the substrate. We deposited a thin silicon-dioxide (SiO_2) layer (3 nm, 10 nm) before the metal-deposition step to change the surface condition from hydrophobic to hydrophilic, resulting in better adhesion between the metal and the substrate. THz time-domain spectroscopy was carried out to measure the transmittance of filters. The insertion losses were 0.56 dB and 0.58 dB and the stop-band attenuations for the first resonance were 22.44 dB and 22.42 dB; the corresponding second resonance values were 24.69 dB and 23.07 dB for filters with pre-deposited SiO2 of 3 nm and 10 nm, respectively. The SiO2 deposition did not limit the good transmission characteristics of the Zeonor substrate as a filter substrate, and it enabled the MMs to stand on the substrate.

8806-89, Session PWed

The optical limiting effect in suspensions astralens

Rimma Zatrudina, Vitaliy Kuzmenko, Volgograd State Univ. (Russian Federation)

A new form of fullerene-conformable nanostructures – the astralens [1] –was investigated. The astralens represent polyhedral multi-shell toroidal carbon nanoparticles a typical dimentions about 150 nm. They have optical strength and thermal stability more than fullerenes, and they have high chemical stability. The astralens are not soluble in any solvent, but they form a stable suspension. The astralens absorption spectrum is monotonous decreased from 400 nm to 1200 nm.

Nonlinear absorption of astralens aqueous suspension was measured using the Nd3+-glass laser at 1064 nm in Q-switching and short-term resonant modulation of losses [2] regimes. The duration of the pulse generation in these regimes makes 100 ns and 1 ns, respectively. The dependence of the transmittance of astralens aqueous suspension versus the incident radiation intensity in the range 100 kW/cm2 – 1 GW/cm2 was measured. Nonlinear transmission appears at the value of intensity about 10 MW/cm2. At the intensity 1 GW/cm2 the initial transmittance is decreased in 4 time. The relaxation time was about 15 ns. Comparison of the obtained experimental results with theoretical calculations showed that the optical limitation is caused by the resonant mechanism of reverse saturable absorption, and nonresonant mechanism of the nonlinear scattering.

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8806-90, Session PWed

Quantum theory of the plasmonic nanolaser

Ilya A. Fyodorov, Moscow Institute of Physics and Technology (Russian Federation); Andrey K. Sarychev, Institute for Theoretical and Applied Electrodynamics (Russian Federation); Alexei Bogdanov, HGST (United States); Andrey N. Lagarkov, Institute for Theoretical and Applied Electromagnetics (Russian Federation); Gennady Tartakovsky, Innovative Optical Solutions (United States)

Surface plasmon nanolasers, also known as SPASERs attract much attention in recent years due to the numerous potential applications in the plasmonics. In this work, we consider the metal horseshoe nanoresonator filled with the active dielectric medium. The size of the considered resonator is much less than the wavelength. On this scale, the plasmon field inside the nanoresonator behaves as a quantum object. The plasmon quantum field is subject of the random external force because of the quantum-mechanical process of the photon absorption in the active medium. Due to the small size of the resonator, the coupling between the plasmon field and an atom of the active medium is anomalous strong. The interaction cannot be considered as just emission and absorption processes. We develop the quantum dynamics of the plasmon field coupled with the active medium. Thus, we consider how the quantum fluctuations influence the process of the luminescence and find how the lasing threshold is changed. The coherence of the light emitted by the plasmon laser is also considered. We predict that the light beams, radiated from non-interacting plasmon nanolasers, could not give the interference pattern. The quantum properties of the nanolaser are important for many applications, such as transmitting and processing optical signals on a scale much smaller than the wavelength.

8806-91, Session PWed

Design of polarization splitter through phase transformation based on transformation optics

Wenyan Yan, Weixing Shu, Hunan Univ. (China)

Within the past a few years transformation optics has been arousing great interest. It provides a general method to manipulate electromagnetic waves by materials. Using it a host of striking electromagnetic devices has been demonstrated, mainly focused on controlling the path of light ray or on molding the phase, such as phase transformers. In that regard we proposed a general method of phase transformation between any two wavefronts through a compact slab (Phys.Rev.A 85,063840:2012). Meanwhile, less work has been devoted to manipulating the polarization.

In this work we will show it is possible to control the polarization through phase transformation based on transformation optics and present a theoretical design of polarization splitter. Usually the polarization splitter is constructed by optically anisotropic media. Being limited by the material parameter values, the split angle is restricted in conventional media and the direction of the output waves can only be tuned by the optical axis or the geometrical shape of the media. In contrast, our present scheme will keep a planar configuration, while the exit wave direction and shape can be manipulated.

In details we firstly realize a phase transformer that is able to deflect a wave into any direction and shape prescribed. For TE and TM waves we choose distinct deflection angles and obtain two sets of material parameters. Since the two sets are independent of each other, they can be fulfilled in a single anisotropic slab that will implement a polarization splitter. The results are further confirmed by numerical simulations.

8806-92, Session PWed

Nanopatterned multilayer hyperbolic metamaterials for spontaneous light emission control

Dylan Lu, Lorenzo Ferrari, Zhaowei Liu, Univ. of California, San Diego (United States)

Light emission process near the metallic surface has been modified through the Purcell effect, but it relies on the matching between spontaneous emission spectra and surface plasmon resonances which are limited by existing metal properties. In this work, we propose nanopatterned multilayer hyperbolic metamaterials (MHMs) for enhancing emission decay rates with improved radiative emission into the far field. By investigating Purcell effect on flat metallic films, flat and nanopatterned MHMs, we demonstrate tunable Purcell enhancement on MHMs across the visible spectrum through the engineering of hyperbolic material properties based on a theoretical model for dipole emitter's interaction with multilayer substrates and confirmed by full-wave electromagnetic simulations. The distribution of three decay channels, radiative emission, plasmonic modes, and lossy-wave component, is also analyzed by varying the emitter-substrate distances and emission wavelengths. The non-radiative nature of dominating plasmonic-mode component in flat MHMs leads to low radiative emission and external quantum efficiency. Nanopatterning into MHMs out-couples plasmonic modes into the far field for increased radiative emission, enabling far-field detection of strong Purcell enhancement. The promise in achieving light emission with both high decay rates and brightness has potential applications in light-emitting devices, single molecule detection, and surface-enhanced Raman spectroscopy.

8806-95, Session PWed

Extending the scaling limit of artificial magnetism using vertical split ring resonator array

Fan Zhou, Chen Wang, Biqin Dong, Cheng He, Cheng Sun, Northwestern Univ. (United States)

Sub-wavelength split ring resonators (SRRs) has attracted much attention in creating artificial magnetism beyond the gigahertz range. However, the breakdown of linear scaling was found at the frequency above 100 THz. The contribution of self-inductance of electrons becomes ineligible when reduce the dimension of the planar SRRs. To overcome this issue, we developed a new route to fabricate vertically aligned SRR array consists of 1D array of metallic nanowires with U-shaped cross-section. Such a vertical SRRs exhibit two unique advantages: 1) it can be excited simultaneously by both the electric and the magnetic field of light at normal incidence; 2) The dramatically increased cross-section area effectively reduces the self-inductance of electrons and the Ohmic loss, successfully extending the scaling of artificial magnetism to the visible spectrum. The numerical simulation confirms the magnetic induced resonance at 408 THz and electrically induced resonance at 571 THz.

The U-shaped SRR array is fabricated using nanotransfer printing (nTP) process. The master mold consists of 1D grating of 150 nm width and center to center distance of 300 nm, based on which elastomeric stamps are prepared by NIL. Then 30 nm Au layer is coated on the elastomeric stamp by two subsequent angular depositions to form the U-shaped cross-section. It is then transferred to an epoxy-coated substrate via selective nTP, forming isolated and upright U-shaped grating structures. The reflectance and transmission spectrum of the SRR array are characterized by optical spectroscopy and the experimental results are in good agreement with numerical simulations.

8806-96, Session PWed

The influence of period between u-shaped resonators on metasurface response at terahertz frequency range

Mikhail K. Khodzitskiy, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Yury E. Terekhov, Lomonosov Moscow State Univ. (Russian Federation); Yaroslav V. Grachev, Egor A. Sedykh, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Last years there has been intense research on metamaterials, which novel electromagnetic responses aren't available in natural materials. Especially there has been an increasing focus on practical applications for metamaterials in the terahertz frequency range [1-3]. Particularly, terahertz wave filters will be key components in the implementation of future terahertz (THz) communications systems, for terahertz sensing of biological and chemical samples, etc. However, for practical applications in industry, the tunability, simplicity, and low cost of THz filters are more favorable and widely demanded. In this paper we study the influence of the period between U-shaped split-ring resonators (SRRs) on the transmission/ absorbtion properties and refraction index of metasurface in THz frequency range (0.1-1 THz) using experiments and numerical simulations. The metasurface are formed by copper element arrays such as U-shaped SRRs. The metasurface is divided on nine parts with different values of the period between resonators. The period varies from 63 to 300 mkm. We fabricated the metasurface on the ZERODUR substrate by the use of ion-vacuum evaporation (the thickness of substrate is of 0.55 mm). Finally, the arrays of split-ring resonators were formed by laser engraving technique. The metasurface electromagnetic responses were characterized by terahertz time-domain spectroscopy. The experimental results reveal the shift in the transmission spectra for the metasurface response and the tuning of absorbtion intensity when the period between U-shaped SRRs changes. The notable change in the

metasurface refractive index produced by plasmon-polariton resonance for period alteration is shown. The experimental results are in consistence with finite-element simulations using COMSOL Multiphysics.

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8806-74, Session 15

All-dielectric nanoantennas and metamaterials *(Keynote Presentation)*

Yuri S. Kivshar, The Australian National Univ. (Australia) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Andrey E. Miroshnichenko, The Australian National Univ. (Australia); Pavel A. Belov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Recent experimental demonstrations of strong magnetic response of silicon nanoparticles in the visible range suggest a novel approach to many problems of nanophotonics where magnetic resonances of all-dielectric nanoparticles can be employed in addition or instead of electric resonances of metal nanoparticles in plasmonic structures. The basic physics of the excitation of magnetic response in high-index dielectric nanoparticles is quite different to that of conventional metallic nanoparticles and split-ring resonators. A magnetic Mie resonance originates from the excitation of a particular electromagnetic mode inside the nanoparticle with a circular displacement current of the electric field. This mode is excited when the wavelength of light is comparable to the particle’s diameter, and it has an antiparallel polarization of the electric field at the opposite sides of the particle

In this talk, we demonstrate novel effects for the interaction of electromagnetic waves with the structures composed of high-index dielectric nanoparticles due to the excitation of the magnetic Mie resonances. We demonstrate interplay of magnetic and electric resonances in such structures, and also discuss several examples including all-dielectric nanoantennas, oligomers of high-index dielectric nanoparticles, and all-dielectric metamaterials, and present several proof-of-principle experiments for the microwave and optical wavelength range. In particular, we predict and describe a novel type of Fano resonances originating from the optically-induced magnetic dipole modes of individual high-dielectric nanoparticles, and compare our results with the corresponding results for plasmonic structures.

8806-75, Session 15

Dielectric resonators for metamaterials *(Invited Paper)*

Aditya Jain, Iowa State Univ. (United States); Philippe Tassin, Iowa State Univ. (United States) and Chalmers Univ. of Technology (Sweden); Thomas Koschny, Costas M. Soukoulis, Iowa State Univ. (United States)

Metamaterials can achieve media with properties unattainable in nature, such as negative index of refraction or giant chirality. Many metamaterials are made out of metallic constituents, but they are plagued by dissipative loss due to conversion of energy to heat in the metal. It has been suggested to replace metallic electric circuits by Mie resonances in dielectric particles, but in general it is difficult to make such particles much smaller than the subwavelength, resulting in periodicity effects. In this talk, we present a novel type of metamaterials consisting of dielectric rather than metallic building blocks and we demonstrate that this can reduce dissipation in metamaterials significantly. We present our experimental work concerning a dispersion-engineered metamaterial based on a meta-atom made from alumina. This metamaterial possesses a resonance with a much larger quality factor than what is normally observed in metal-based metamaterials. We also show how our dielectric meta-atom can be used to create metamaterials with negative permittivity or negative permeability. The resulting structures can be modified to obtain metamaterials with a variety of properties.

8806-76, Session 15

High-contrast meta-structures for sub-diffractional light control *(Invited Paper)*

Jingjing Li, Univ. of Illinois at Chicago (United States)

The peculiar properties of metamaterials and their capability in making various devices, such as superlenses, sub-wavelength sized cavities, etc., are attracting a great deal of research interests. Currently, in the optical frequency domain, metamaterials are usually constructed from plasmonic inclusions, but the related ohmic loss has been a crucial factor limiting the performance of many of the devices. We show that the resonant phenomena related to dielectric structures of relatively high refractive index (such as silicon, n~3.5) can be harnessed to realize many of the devices once assumed to be only possible on metamaterials. The devices that will be discussed in the presentation include dielectric superlens with sub-diffraction focus; Optical cavities and waveguides of sub-wavelength mode size with the optical field staying in open space, thus freely accessible by particles and other agents. We show that optical antennas designed from some of the cavities can be coupled to a radiating dipole and distribute the radiation to the endfire direction. Some of the devices are designed through parallel stochastic optimization based on genetic algorithm which will also be introduced in the presentation.

8806-77, Session 15

Transformed cladding waveguides: confining light with all-dielectric metamaterials

Saman Jahani, Zubin Jacob, Univ. of Alberta (Canada)

Massive efforts over the last decade have been driven by miniaturization and integration of electronics and photonics on the same platform. Plasmonic waveguides suffer from absorption while photonic crystal waveguides and slot waveguides suffer from huge cross talk between closely spaced waveguides.

Here, we introduce a new class of metamaterial waveguides capable of dense photonic integration. We show that all-dielectric metamaterial claddings (epsilon > 1, mu = 1) can strongly confine light inside conventional low-index dielectric waveguides. To design the metamaterial claddings, we introduce the concept of transforming optical momentum for controlling evanescent waves. We show that these transformations lead to a class of metamaterials with dual electric and magnetic anisotropy along with giant birefringence which provide the ideal quasi-transverse electromagnetic mode propagation inside a glass core. However, magnetism at the telecommunication wavelength is a major challenge and we show that strong confinement of the electric energy of a waveguide mode can be achieved with lossless semiconductor metamaterials. The proposed practical lossless Transformed Cladding Waveguides show an order of magnitude decreased cross-talk as compared to conventional waveguides making them suitable for multiple applications in dense photonic integration and nanophotonic devices. Finally, we propose practically achievable all-dielectric metamaterial waveguides using lossless semiconductors with increased power confinement in the core for dense photonic integration

8806-78, Session 15

Probing the transition between the long-wavelength and the short-wavelength regimes of light propagation in all-dielectric metamaterials

Eric Cassan, Institut d'Électronique Fondamentale (France) and CNRS-Fonctions Optiques pour les Technologeis de l'information (France); Jean Dellinger, Univ. de Bourgogne (France); Xavier Le Roux, Khanh Van Do, Charles Caer, Institut d'Électronique Fondamentale (France) and CNRS-Fonctions Optiques pour les Technologeis de l'information (France); Frédérique A. de Fornel, Benoit Cluzel, Univ. de Bourgogne (France) and CNRS-Fonctions Optiques pour les Technologeis de l'information (France)

The transition between the long-wavelength and the short-wavelength regimes of light propagation in all-dielectric metamaterials is experimentally investigated using a hyperspectral near-field scanning microscope technique applied to a strong index contrast graded photonic crystal structure. Our measurements lead to an invariant quantity "λ/n" of only 1.78 times the photonic crystal lattice period as the criterion for the possible application of homogenization theories. Fourier decomposition of the photonic crystal Bloch waves allows interpreting the observed sudden transition between the two light regimes as a wavevector shift of the main partial plane wave at the crossing of the wavevector path with the first Brillouin zone of the photonic crystal. As a whole, these findings indicate the robustness of the homogenization approach of all-dielectric metamaterials and also suggest that the sharp transition between the two light propagation regimes could be profitably combined in graded optical artificial materials.

8806-97, Session 15

Fishnet metamaterial with broadband double negative refractive index in visible spectrum

Shiwei Zhou, Xiaodong Huang, RMIT Univ. (Australia); Qing Li, The Univ. of Sydney (Australia); Yi Min Xie, RMIT Univ. (Australia)

By optimizing the shape and scale of the perforated holes as well as the depth of metal-dielectric-metal layers, we designed a double fishnet metamaterial exhibiting 253 nm bandwidth of negative refractive index covering from 640 to 893 nm in wavelength, the widest one has even been reported. In visible spectrum, it spreads red and infrared regimes which are equivalent to 140 nm bandwidth. Moreover, the permittivity and permeability of this novel metamaterial are simultaneously negative from 647 to 755 nm, 5.7 times larger than formerly reported 19 nm in visible range. This pattering technique can be readily extended to other promising systems.

8806-79, Session 16

Recent experimental progress on quadruple-helix based metamaterials *(Invited Paper)*

Johannes Kaschke, Justyna K. Gansel, Joachim Fischer, Michael Thiel, Martin Wegener, Karlsruher Institut für Technologie (Germany)

Metamaterials based on metal helices have been introduced as broadband circular polarizers. For arrays of single helices however, the end of the helix wire together with the helix center defines a direction in space that breaks the rotational symmetry and leads to polarization conversion. Based solely on symmetry considerations we show that recovering four-fold rotational symmetry with N=4 intertwined helices circular polarization conversions can be eliminated. However, the operation mechanism is fundamentally different from single helices and without absorption of the constituent metal no circular polarization capability can be seen. The analysis is only based on four-fold rotational symmetry and time-reversal symmetry. The symmetry with respect to inverting the direction of propagation is not considered and a substrate will not change the analytical results. We compare these analytical findings to extensive numerical calculations.

Furthermore, we present current progress in the fabrication of N-helix metamaterials. We create polymer templates for subsequent electrochemical deposition of gold using STED inspired direct laser writing (STED-DLW). The major drawback of STED-DLW however, is the lack of a positive-tone photo-resist. We employ a negative-tone photo-resist instead by writing part of the complementary structure. Using STED-DLW, a highly enhanced aspect ratio can be achieved and with the increased axial resolution these inverse structures become feasible. The obtained hollow tubes are subsequently filled with gold by electro-chemical deposition during which a transparent indium-tin-oxide layer on the glass serves as the cathode.

8806-80, Session 16

Rotational optomechanics of metamaterials *(Invited Paper)*

David A. Powell, Mingkai Liu, The Australian National Univ. (Australia); Mikhail Lapine, The Univ. of Sydney (Australia); Ilya V. Shadrivov, Yuri S. Kivshar, The Australian National Univ. (Australia)

Development of nonlinear metamaterials have received new momentum with the recent emergence of structural nonlinearity, which opens rich opportunities by enabling new degrees of freedom in metamaterial design. For example, magnetoelastic metamaterials have demonstrated a nonlinear interaction between mechanical and electromagnetic subsystems, providing unusual patterns of nonlinear response. Alternatively, conformational nonlinearity has been achieved by designing a link between the electromagnetic, mechanical and thermal responses in helical metamaterial elements. Our most novel approach - metamaterials with internal rotation - is based on exploiting an easily controllable and highly sensitive mechanical feedback: twisting of an elastic wire. By using this feedback scheme, we have been able to provide a direct coupling between electromagnetic torque, induced by the incident waves in the system of split-ring resonators, and the mutual angle between them, which dynamically changes through their mutual rotation, until balanced by the elastic torque. This nonlinear mechanism results in a strongly nonlinear response and leads to a very pronounced bistability. We provide a complete analytical and numerical evaluation of the properties of this system, and confirm our findings with the proof-of-principle microwave measurements. We were able to obtain a robust bistable behaviour in experiments, showing an excellent agreement with theoretical predictions. Importantly, the general logic of our design is scalable across frequencies, implying that the corresponding nonlinear mechanism can be implemented in a wide frequency range. We believe that our results provide a valuable inspiration for the emerging area of metamaterial optomechanics, and are important for its further development.

8806-81, Session 16

Complex chiral plasmonics *(Invited Paper)*

Mario Hentschel, Harald W. Giessen, Univ. Stuttgart (Germany)

We demonstrate a strong chiral optical response in stacked arrangements of plasmonic nanostructures. We show that three-dimensional arrangements of plasmonic "meta-atoms" only exhibit a chiral optical response if similar plasmonic "atoms" are arranged in a handed fashion as we require resonant plasmonic coupling. Moreover, we demonstrate that such particle groupings, similarly to molecular systems, possess the capability to encode their three-dimensional arrangement in unique and well-modulated spectra, making them ideal candidates for a three-dimensional chiral plasmon ruler. Furthermore, we discuss

the onset of a broadband chiral optical response in the wavelength regime between 700 nm and 3500 nm upon charge transfer between the nanoparticles. We show in experiment and simulation that this response is due to the ohmic contact between adjacent particles which causes a strong red-shift of the fundamental mode. The geometrical shape of the resulting fused particles allows for efficient excitation of higher order modes. Calculated spectra and field distributions confirm our interpretation and show a number of interacting plasmonic modes. Finally, we will discuss plasmonic diastereomers which consist of multiple chiral centers. We find that the chiral optical response of the composite molecules can be traced back to the properties of the constituting building blocks. We demonstrate that the optical response of complex chiral plasmonic systems can be decomposed and understood in terms of fundamental building blocks, offering simple and straightforward design rules for future applications such as chiral optical elements and enantiomer sensors.

8806-83, Session 16

Effect of rotational symmetry on the optical rotation of using asymmetrical nanostructures

Y. L. Hor, W. K. Phua, A*STAR Institute of High Performance Computing (Singapore); Yanjun Liu, Eunice S. P. Leong, S. Wu, A*STAR Institute of Materials Research and Engineering (Singapore); Iftikhar Ahmed, Ching Eng J. Png, Eng Huat Khoo, A*STAR Institute of High Performance Computing (Singapore)

In this paper, we rotate an array of asymmetrical gammadion to investigate its effect on the chirality and sensitivity detection of biomolecular structures. The gammadion structure is made up of gold material on a glass structure and immersed in water. The gammadion array has a pitch of 700 nm with square arrangement and has right handed direction. The chirality of the un-rotated array is first determined by measuring the circular dichroism (CD) spectrum. The spectrum shows three resonance CD modes, which represent Bloch period mode and surface plasmonic resonance modes (SPR). The array is then turn to different angles with respect to the horizontal axis. It is observed that the CD spectra at different angles are different. The Bloch mode is red-shifted to longer wavelength while the SPR mode is blue-shifted. This is due to the rotation of array, which changes the optical axis, optical symmetry and arrangement from square to hexagonal. We also compare with the case where each asymmetrical gammadion is rotated and with fixed period, instead of turning the whole array. In the second case, the rotated gammadion resulted in larger wavelength shift of the CD spectra. In addition, the CD also increases by an average of 20%, given a larger absorption difference between the left and right handed circular polarized light. The results play an important role in the identification of biomolecules structures, synthesizing drug with required handedness and wide application to different class of protein molecules.

8807-1, Session 1

All-semiconductor plasmonics for mid-IR applications *(Invited Paper)*

Thierry Taliercio, Vilianne Ntsame Guilengui, Laurent Cerutti, Jean-Baptiste Rodriguez, Eric Tournié, Univ. Montpellier 2 (France)

Surface plasmon polaritons result of the strong coupling between an electromagnetic wave and the collective oscillation of free electrons of a metal. They are generated at the interface between a metal and a dielectric. They present actually a great interest because of their potential applications in the fields of metamaterial or metasurfaces, enhanced photonic devices properties, nanophotonics integrated circuits and nano-bio-photonics. All these applications rely on the use of gold resonators. Because of the need to integrate plasmonic functionalities to semiconductor devices and to keep high field exaltation at the metal/dielectric interface for mid-IR application, it is really attractive to use highly doped semiconductors. The plasma frequency as the magnitude of the permittivity of the highly doped semiconductor can be controlled via its doping level. We propose experimental study of stripe arrays of doped and encapsulated in un-doped semiconductors. The samples consist of a layer of 50 or 100 nm of lattice-matched InAsSb (Si at 1020 cm-3) grown by Molecular Beam Epitaxy (MBE) on a GaSb substrate. InAsSb arrays are realized by holography and wet or dry etching. The typical grating period is 540 nm and the width of InAsSb stripes varies from 210 to 90 nm. The encapsulating layer of GaSb is performed by MBE on the InAsSb grating. Angular dependent reflectance experiments with polarized light allowed identifying localized surface plasmon. Adjusting the doping level and the stripe's geometry allows controlling the wavelength of localized surface plasmon resonances.

8807-2, Session 1

On the detection of characteristic optical emission from electronically coupled nanoemitters

David S. Bradshaw, Jack S. Ford, David L. Andrews, Univ. of East Anglia Norwich (United Kingdom)

Optical emission from an electronically coupled pair of nanoemitters is investigated, in a theoretical analysis prompted by experimental work on oriented semiconductor polymer nanostructures. Three physically distinct mechanisms for photon emission by such a pair, positioned in the near-field, are identified: emission from a pair-delocalized exciton state, emission that engages electrodynamic coupling through quantum interference, and correlated photon emission from the two components of the pair. Each possibility is investigated, in detail, by examination of the emission signal via explicit coupling of the nanoemitter pair with a photodetector, enabling calculations to give results directly tailored for experiment. The analysis incorporates both near- and far field properties (determined from the detector-pair displacement), so that the framework is applicable not only to a conventional remote detector, but also a near-field microscope setup. The determined results are found to be strongly dependent on geometry and selection rules. This program of work paves the way for investigation of pairwise coupling effects in the emission from nanoemitter arrays.

8807-3, Session 1

NIR emitting gold nanorods: mechanism underlying the principle of emission in a metal-metal hybrid nano system

Lakshmi V. Nair, Ramapurath S. Jayasree, Sree Chitra Tirunal Institute for Medical Sciences & Technology (India)

Gold quantum cluster (GQC) and gold nano rods (GNR) are two different nanostructures of one of the most fascinating noble metals. These two nanostructures have exclusive optical properties which is attributable either to its size or shape. Gold quantum clusters are widely accepted for its extremely smaller size (~ atomic size) and the inherent fluorescence property due to quantum confinement effect. Gold nanorods, on the other hand attribute certain additional properties like NIR absorption because of the anisotropic nature and hence is an ideal candidate for photo thermal ablation.

Metallic gold impart fluorescence quenching of fluorochromes when they are in close proximity, where as metal enhanced fluorescence is exhibited at nanocluster scale where free electron model of metallic behaviour is predicted. Moreover, gold clusters are more stable and non photo bleachable.

We have developed a hybrid system of GQC and GNR, without compromising their individual properties. Glutathione protected quantum cluster with emission around 750 nm and GNRs with different aspect ratios whose absorption cross section overlaps with that of the emission of clusters were synthesized. A combined system was developed which exhibits fluorescence in the near infrared region leaving the rod structure intact. This was achieved by tuning the reaction conditions during the development of the GQC-GNR system. We discuss the mechanism underlying the fluorescence exhibited by the hybrid system in the context of the reaction conditions. This is the first report on a metal-metal combined nano system which can be used for FRET studies based on the donor-acceptor interaction.

8807-4, Session 1

Molecular nature of PbS nanoclusters attached on the silica spheres

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Abstract

The mixture of phenyltrimethoxysilane (PTMS) and mercaptopropyltrimethoxysilane (MPTMS) has been covalently bonded to the surface of the monodisperse silica spheres to attach the PbS nanoclusters. The Fourier transform infrared (FTIR) spectra of the modified silica spheres (MSSPh) with PTMS and MPTMS clearly indicates the phenyl ring and carbohydrate absorption band. The FTIR spectra of MSSPh after attaching the Pb2+ and converting Pb2+ to PbS show the characteristic absorption peaks. The stopband of unmodified silica spheres located at 830 nm. However, the stopband disappears after surface modification and PbS formation due to the hydrophobic nature of the silica spheres. The field emission scanning electron microscope images of the MSSPh and MSSPh-PbS show similar surface texture. The compositions of the MSSPh-PbS obtained by energy dispersive spectroscopy include silicon, oxygen, carbon, sulfur and lead with the atomic ratio (weight ratio) of 33.34 (46.31), 32.60 (25.80), 32.90 (19.55), 0.40 (0.64) and 0.75 % (7.70 %), respectively. The photoluminescence (PL) spectrum shows several luminescence peaks between 600 to 840 nm. The PL results indicate that the PbS nanoclusters (NCs) may have molecular characteristics with this growth process. A precisely controlled growth can be achieved by extensive washing and centrifuge processes.

8807-5, Session 1

Ultracompact metamaterials-based polarization converter for photonics at telecom wavelength

Loïc O. Le Cunff, Alexandre Vial, Rafael Salas-Montiel, Sylvain Blaize, Aurélien Bruyant, Univ. de Technologie Troyes (France); Anatole Lupu, Institut d'Électronique Fondamentale (France); Gilles Lérondel, Univ. de Technologie Troyes (France)

Over the past decades, advances in fabrication and characterization techniques have allowed Nanophotonics to emerge, and we are now at a point where nanophotonic devices are making their way into common products. However, there is still a lot of research to be done in that field, especially on new components. New compact and efficient components for nanophotonics are thus of great importance. The studies presented here have been done as part of the ANR METAPHOTONIQUE project, which first purpose is to design metametarials-based structures operating at telecommunication wavelength and integrated with SOI technology (Silicon on Insulator).

We present results of 3D simulations, done through the FDTD method, of a device operating at 1.55 micron and which allows for the rotation of guided light's polarization. That device efficiency is quantified in the case where it is crafted on top of a planar waveguide, and we show that it can convert up to 30% of the energy over a length shorter than that wavelength, making it a compact and efficient device. The physics behind that polarization rotation and the limits of that device are discussed, and its behavior on a waveguide of finite width is presented.

8807-6, Session 2

Transparent conductive oxides for light emission, plasmonics, and metamaterials *(Invited Paper)*

Luca Dal Negro, Boston Univ. (United States)

Transparent conductive oxides (TCOs) are a broad class of organic and inorganic materials exhibiting both optical transparency and electrical conductivity simultaneously. Zinc oxide (ZnO) is the most promising candidate for optoelectronic applications due to its large band-gap, high refractive index, low cost, and Si compatibility. We propose ZnO as a novel material platform for telecom and bio-compatible optoelectronics, plasmonics and solar cell devices.

First, we demonstrate multiband near-IR emission of Er and Nd in Si-rich ZnO thin layers under optical and electrical injection. We have investigated the rare earth (RE) excitation mechanism, driven by energy transfer from the ZnO band-gap and its optical-active defect centers. Moreover, we introduce Si in the matrix, and we demonstrate and quantify efficient Si-mediated energy sensitization of the rare earth ions. Si influence on the RE emission lifetime is elucidated as well. A proof-of-concept electroluminescent device based on Er-doped Si-rich ZnO with very low injection current density and turn-on voltage will be shown [1].

In addition, Aluminum-doped ZnO (AZO) has been demonstrated as a transparent and conductive plasmonic material in the near-IR wavelength range. In this talk, I will address opportunities and advantages of AZO and other TCOs as a metal-free Si-compatible platform for novel metamaterials-based devices towards the engineering of enhanced light emitting devices and broadband absorbing solar cells.

[1] E. F. Pecora, T. I. Murphy, and L. Dal Negro, Appl. Phys. Lett. 101, 191115 (2012).

8807-7, Session 2

ZnO as an effective fluorescence sensor for nitroaromatic derivatives

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Zinc Oxide (ZnO) is an interesting wide bandgap semiconductor with various applications in medicine, electronics, acoustics and optics. In particular, ZnO is extensively investigated as material for the detection of a great number of gases and vapors. Ongoing research primarily focuses on the study of changes in the electric and acoustic properties of ZnO in presence/absence of gases. However, few studies have addressed the quenching (i.e. decrease) of the ZnO luminescence as a transducing technique for sensing applications. We report on the luminescence quenching of ZnO nanowires for TNT vapor detection. Vertically aligned arrays of ZnO nano-wires, with a high aspect ratio (65 nm radius and 1.2 µm height) are grown by metalorganic chemical vapor deposition. Photoluminescence (PL) measurements were realized in the presence/absence of 2,4-Dinitrotoluene (DNT) vapor, an impurity found in TNT. The quenching response of the nanowires is compared to that of a ZnO thin film. While both the thin film and the nanowires exhibited a decrease in the PL intensity, the nanowires present a faster (50 % quenched in 40 s) and more efficient response (95% quenching efficiency) than the thin film (only 15% quenching efficiency). The difference between the quenching response of the nanowires and the thin film is interpreted using Monte-Carlo simulations taking the exciton diffusion length and mean free path as parameters. The experimental results along with the simulations show the importance of nanostructured materials for enhanced sensing response. Moreover, this study reveals the great potential of using ZnO nanowires for TNT vapor detection.

8807-8, Session 2

Infrared to green and red frequency upconversion of Er3+/Tb3+/Eu3+ co-doped Y2O3 nanocrsystals

Geraldo Sobral, UFAL (Brazil); Maria Gomes, UFS (Brazil); Geovana Webler, UFAL (Brazil); Jhon Avila, José Joatan Rodrigues Jr., UFS (Brazil); Jandir M. Hickmann, Márcio A. R. C. Alencar, UFAL (Brazil)

Rare earth-doped nanocrystals (REDN) are among the most promising systems for luminescent applications in nanoscale domain due to their capability of convert infrared excitation into new higher frequencies fluorescence. In this work, we produced yttrium oxide nanocrystals (Y2O3) co-doped with Er3+, Tb3+ and Eu3+ ions and characterized intense infrared to red and green upconversion (UC) emissions. observed when this system was excited by a Ti:Sapphire laser tuned in the range of 792 and 820 nm. The Y2O3 REDN were produced via PVA-assisted sol-gel route, in which polyvinyl alcohol is employed in the polymerization step. The resulting sol was calcined in a temperature range of 400 and 1000 °C for 5 hours. DTA/TG and XRD measurements were employed to investigate the formation of crystalline phase. The particles' size and morphology were investigated using a field-emission scanning electron microscopy. We observed that the sample calcined at 1000 oC was composed by crystals with 34.3 nm diameter. From the fluorescence measurements we identified green UC associated to Er3+ and Tb3+ transitions and red emission due to the Er3+ and Eu3+ transitions. We also observed that the intensities of green luminescence bands vary quadratically with the laser power, which indicates that a sequential two laser photons absorption process of Er3+ gives the main contribution to the observed green UC, while energy transfer mechanisms between Er3+- Er3+ and Er3+-Eu3+ ions are the main responsible for the observed red UC. Our results indicate that this synthesis method can produce efficient nanophosphors useful for luminescent photonic applications.

8807-9, Session 2

Structural, optical, and vibrational properties of ZnO nanorods embedded in polymer matrix

Udayabhaskar Rednam, Balasubramanian Karthikeyan, National Institute of Technology, Tiruchirappalli (India)

ZnO nanorods were synthesized by refluxing method. The prepared ZnO nanorods were carefully characterized using SEM, TEM, XRD and UV-visible and photoluminescence spectrophotometer. ZnO nanorods with hexagonal wurtzite structure were loaded into PVP matrix inorder to get polymer nanocomposite films. The properties of the as-prepared ZnO:PVP composite films are characterized by X-ray diffraction (XRD), thermo gravimetric analysis (TGA), Fourier transform infrared spectroscopy (FTIR), UV-visible and Photoluminescence studies. Band gap of wurzite ZnO gets affected after loading into PVP matrix. TGA studies given the information about thermal stability of these films. The interaction between PVP and ZnO can be understood from the FTIR studies. PL studies provides the details about different luminescence centers identified in the PVP:ZnO polymer nanocomposite films.

8807-28, Session PWed

Enhanced infrared absorption on metal nano clusters and structures

Jae Hong Park, National Nanofab Ctr. (Korea, Republic of)

The intensification of infrared-active vibration modes of molecules in close proximity to nanometer-thick metal films, commonly known as surface-enhanced infrared absorption (SEIRA), is receiving increased attention from both a phenomenological and practical viewpoint. The resonant excitation of Plasmon in metallic nanostructures can provide large field enhancements on the surfaces of metals, which in turn provide dramatic increases in the detected spectroscopic signals for molecules adsorbed on their surfaces. The most widely used surface enhanced spectroscopy (SES) is surface enhanced raman scattering (SERS), where the electromagnetic enhancement factor is proportional to the fourth power of the field incident on the molecule.

Recently there has been a resurgence of interest in another type of SES, surface enhanced infrared absorption. It has been widely applied to surface trace analysis, bio-sensing, electro sorption, and electro catalysis because of its significant amplification of surface signal and simple surface selection rule. The surface enhanced infrared absorption can be observed easily on metal island films prepared by vacuum evaporation or sputtering and electrochemical or electroless deposition. Metal colloids also support the enhancement. Like surface-enhanced Raman scattering (SERS), SEIRA is chiefly of electromagnetic origin, that is, due to an increase in the local optical field exciting the adjacent molecules.

Metal nano clusters much smaller than the wavelength of light facilitate the interaction of the infrared radiation with the metal and adsorbed molecules, resulting in the enhancement. It was explained that the enhancement is greatly affected by the size, and planer density of metal nano clusters compared with metal nano films. Phenomenological and theoretical difference of infrared absorption in broad ranges of wave length including near field to far field infrared rays between metal nano clusters and metal nano films.

8807-29, Session PWed

On a simplified analysis of the external photoelectric effect from quantum wells, wires, and dots of nonlinear optical and optoelectronic nanostructure materials

Subhamoy Singha Roy, JIS College of Engineering (India); A. Singha Roy, School (India)

It has been found taking quantum confined Hg1-xCdxTe, CdGaAs2 and In1-xGaxAsyP1-y lattice matched to CdS, InP and stressed InSb as examples that the external photoelectric effect exhibits plateaus as function of incident photon energy, which is vital from experimental point of view. The numerical results of quantum confined optoelectronic III-V degenerate semiconductors form the special case of my generalized analysis.

8807-30, Session PWed

Optical properties and aging of PbS quantum dots embedded in a porous matrix

Aleksandr P. Litvin, Peter S. Parfenov, Elena V. Ushakova, Anatoly V. Fedorov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Mikhail V. Artemyev, Anatoly V. Prudnikau, Belarusian State Univ. (Belarus); Ivan D. Rukhlenko, Monash Univ. (Australia); Alexander V. Baranov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Close-packed nanocrystal systems based on lead chalcogenide semiconductor quantum dots (QDs) attract much attention due to the possibility to utilize them in a variety of optoelectronic devices, such as photovoltaic elements, LEDs and lasers, and photodetectors. We demonstrate a low-cost effortless method for creation of close-packed nanocrystal systems in porous matrix. The samples thus obtained demonstrate linear dependencies of optical density and luminescence intensity on the QDs concentration and perfect homogeneity. Optical properties of PbS QDs with diameter of 3–8.5 nm embedded in a porous matrix were studied using absorption and steady-state and time-resolved photoluminescence spectroscopy. Luminescence band demonstrate slight red shift increased with rising of QDs concentration, which can be caused by FRET between nominally monodispersed PbS QDs. Measured average room-temperature luminescence lifetimes are size-dependent, increase with decreasing of QDs size and lie between 435 and 58 ns for close-packed PbS nanocrystals systems with QDs of 3.0 and 7.4 nm in diameter, respectively. The aging behavior of PbS QDs in a porous matrix was explored for different sizes of QDs. Large blue shift in luminescence spectra accompanied by increasing of luminescence lifetimes for small and medium QDs after a month of storage indicates the oxidation and decreasing of QDs size. Close-packed nanocrystal systems made from PbS QDs larger than 5 nm are found to be stable in aerobic atmosphere.

8807-32, Session PWed

Spectroscopy of intraband optical transitions in an anisotropic semiconductor nanocrystals

Vadim K. Turkov, Anvar S. Baimuratov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Ivan D. Rukhlenko, Monash Univ. (Australia); Alexander V. Baranov, Anatoly V. Fedorov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Nonspherical semiconductor nanocrystals may exhibit strongly anisotropic photoluminescence and absorption due to the intraband transitions, whose matrix elements depend critically on the envelope wave functions of the confined electrons and holes. We theoretically demonstrate that this anisotropy may be used as the basis for a new type of polarization spectroscopy, enabling one to reliably determine the shape and spatial orientation of individual nanocrystals, as well as providing important information on the symmetry of quantum states involved in optical transitions.

8807-33, Session PWed

Effect of temperature on photoexcited charge carrier dynamics in Si-NCs/SiO2 superlattices

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At present most commercial electronic integrated circuits and devices are fabricated from bulk silicon. However, this material is not useful for fabricating photon emitters because of its indirect band gap. On the other hand, silicon nanocrystals (Si-NCs) have attracted attention over the last years for their efficient light emission. Si-NCs not only have potential applications for optoelectronic devices (silicon-compatible light sources), but also are one of the most promising materials for solar cells (non-toxic absorber material in third generation photovoltaics), biosensors and non-volatile memories. From the application point of view, one of the most suitable materials would be Si-NCs in a SiO2 matrix, which provides a stable and easily achievable surface passivation. The studied samples were prepared by evaporation of SiOx/SiO2 superlattices and subsequent thermally induced phase separation. The dynamics of photoluminescence (PL) was measured by a streak camera on microsecond time scale. The stretched-exponential PL decay with spectrally and temperature dependent coefficients was observed. The time-resolved measurements were completed by a standard time-integrated PL. We show a strong influence of temperature and excitation intensity on the PL spectrum. The results will be interpreted in terms of carrier trapping and compared with those reported on Si-NCs prepared by other techniques.

8807-34, Session PWed

Nonradiative resonant energy transfer between PbS QDs in porous matrix

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Resonant nonradiative energy transfer (FRET) between lead sulfide quantum dots with different sizes embedded in porous matrix is observed. Information on the availability and efficiency of FRET in systems with different relative ratio QD-donor (QDD) and QD-acceptor (QDA) is obtained by analyzing the changes in donors and acceptors luminescence intensity in steady-state and time-resolved fluorescence experiments.

Quantum dots with size 4.8 nm (QDD) and 6.2 nm (QDA) are obtained by hot-injection method. Quenching of QDD PL and enhancement of QDA PL with increasing QDA concentration in the mixture of QDs caused by FRET are observed. At the same time, the relative QDA PL intensity decreases with increasing acceptor concentration in the matrix. It is concluded that the FRET efficiency depends on the molar ratio QD-donor/QD-acceptor and the energy transfer from the donor to the acceptor carries on several channels.

We observe biexponential PL decay with lifetimes of 155 ns and 80 ns, typical for the individual QDD and QDA in the matrix, respectively. With increase of the acceptor concentration in the matrix the contribution of the donor PL decay decreases. This indicates that the energy transfer in the studied systems is determined by static quenching, specific for direct contact between QDD and QDA in the close-packed ensembles of the QDs.

8807-35, Session PWed

Tunable luminescent properties of AgInS2/ZnS and AgInS2/ZnS at ZnS core-shell particles

Théo Chevallier, Gilles Le Blevennec, Sonia De Sousa Nobre, Frederic Chandezon, Commissariat à l'Énergie Atomique (France)

AgInS2/ZnS (AIZS) nanoparticles are luminescent semiconductor nanocrystals that are good candidates for the development of new white light emitting diodes because of their low toxicity compared to CdSe quantum dots. Moreover, the optical properties of AIZS particles are easily tuned by changing the AgInS2/ZnS molar ratio. Indeed, the luminescence of AIZS is primarily induced by the defects in their structure leading to a donor-acceptor luminescence mechanism.

In this work, we present the recent results of our investigations of the electronic structure of these nanomaterials in order to optimize the photoluminescence quantum yield associated with their light conversion properties. XRD spectra and TEM images confirmed the successful synthesis of crystalized AIZS nanocrystals with a chalcopyrite structure. AIZS nanocrystals with various compositions were successfully synthesized leading to the evolution of their luminescence properties with composition. Donor-acceptor type emission was confirmed by stationary photoluminescence measurements. Absorbance, time resolved spectroscopy, UPS and ESR measurements were used to probe the electronic structure of AIZS particles with a close look at the influence of defects.

With the help of TGA measurements, the growth of a controlled layer of semiconductor on the already made particles was achieved. ZnS coated AIZS nanocrystals gave insights on the electronic structure of the surface defects and their specific role in the donor-acceptor emission. Moreover reliability and thermal stability of AIZS and ZnS coated AIZS particles were studied by incorporating them in a standard LED device.

8807-36, Session PWed

Time-resolved pump–probe spectroscopy of intraband absorption by a semiconductor nanorod

Mikhail Y. Leonov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Ivan D. Rukhlenko, Monash Univ. (Australia); Anatoly V. Fedorov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The employment of anisotropic nanoparticles offers novel degrees of freedom in fabrication of complex geterosystems on the nanoscale. Despite the many practical benefits associated with the nanoparticles' anisotropy, the physical properties and electronic dynamics of anisotropic nanoparticles are still poorly understood. This gap in understanding may be filled via the analysis of the nanoparticles' response measured using the time-resolved pump–probe optical spectroscopy. Such an analysis must rely on a solid theoretical foundation of this spectroscopic technique tailored to study anisotropic nanoparticles, and may eventually put an end to the long-lasting discussion on the dominant relaxation mechanisms of nanoparticle electronic subsystem. In this work, we develop a theory of pump–probe optical spectroscopy based on the pump-pulse-induced transient intraband absorption of the probe pulse inside an anisotropic semiconductor nanorod. Our theory assumes that the carrier frequencies of the pump and probe pulses are close to the resonances with interband and intraband transitions, respectively. The evolution of the electronic states of the nanorod is described using the density matrix formalism. We elucidate the experimental conditions under which the dependence of the absorbed energy on the delay between probe and pump pulses is given by an exponential function, with the exponent inversely proportional to the lifetime of the electronic state.

8807-37, Session PWed

Hierarchical ZnO/MgO nanostructure for enhancing light emission of vertical light-emitting diodes

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Nanostructured vertical light-emitting diodes (V-LEDs) with a very dense forest of vertically aligned ZnO nanowires on the surface of N-face n-type GaN are reported with a dramatic improvement in light extraction efficiency (~3.0x). The structural transformation (i.e., dissociation of the surface nitrogen atoms) at the nanolevel by the UV radiation and Ozone treatments contributes significantly to the initial nucleation for the nanowires growth due to the interdiffusion of Zn into GaN, evident by the scanning photoemission microscopy (SPEM), high-resolution transmission electron microscopy (HR-TEM), and ultraviolet photoelectron spectroscopy (UPS) measurements. This enables the growth of densely aligned ZnO nanowires on N-face n-type GaN. This approach shows an extreme enhancement in light extraction efficiency (>2.8x) compared to flat V-LEDs, in good agreement with the simulation expectations (~3.01x) obtained from 3D finite-difference time-domain (FDTD) tools, explained by the wave-guiding effect. The further increase (~30%) in light extraction efficiency is also observed by forming a hierarchical ZnO/MgO Nanostructure as a form of 'needleleaf tree' on VLEDs. The growth mechanism of nanolscale needleleaf tree is also investigated.

8807-38, Session PWed

Quantum analysis of the density-of-states function with dispersion relation in semiconductors physics

Subhamoy Singha Roy, JIS College of Engineering (India)

The famous consequence of the DOS for the parabolic energy band has been obtained under certain limiting conditions from our generalized term in the nonappearance of external force.

8807-39, Session PWed

Low-threshold Raman laser from an on-chip, high Q polymer microcavity

Bei-Bei Li, Qihuang Gong, Yun-Feng Xiao, Peking Univ. (China)

No Abstract Available

8807-10, Session 3

Optical properties of two-dimensional (2D) CdSe nanostructures

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Until recently, a very little attention has been given a two-dimensional (2D) colloidal semiconductor nanocrystals or nanoplatelets (NPs), spatial quantization of excitons in which is only in one dimension. Most of studies to date were focused on the mechanisms of growth and morphology of the 2D-nanocrystals. Works devoted to the electronic and phonon structures, depending on the thickness of the NPs, are virtually absent. In this work, the resonant and non-resonant Raman spectra of CdSe nanoplatelets with thickness of 5, 6, and 7 monolayers with the fundamental exciton transition at 460, 515 and 550 nm, respectively, were obtained. Micro-Raman spectra of the CdSe NPs with different numbers of monolayers demonstrate characteristic peaks at frequencies of ~ 180, 203, 230, 370, 406 and 470 cm-1. Here peaks at ~ 180 cm-1 and 203 cm-1 are associated with the SO and LO phonon modes of the NPs where as the peaks at 370 cm-1 and 406 cm-1 with their overtones. It was found that the frequencies of the LO-phonon and its overtone bands monotonically decrease with the platelets thickness that was associated with the effect of spatial confinement of optical phonons like that for CdSe quantum dots.

8807-11, Session 3

Optical and vibrational studies of ZnO nanostructures with silver colloids

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We report Optical and vibrational properties of Ag doped ZnO nanoparticles. Ag/ZnO is prepared by using simple room temperature sol gel synthesis and influence of silver on ZnO is studied. Structural and optical properties are characterized by X-ray diffraction, Fourier transform IR (FTIR), Micro Raman, UV-visible, and photoluminescence spectroscopy for both pure ZnO (0 % Ag) and Ag/ZnO (5 % ZnO) nanostructures. Morphology studies are carried out using SEM and TEM. Uv-Vis results shows absorption related to band gap of ZnO along with the SPR (surface Plasmon resonance) band related metallic silver nanoparticles. The intensities of fingerprint Raman lines of ZnO nanocrystals were increased remarkably due to Ag doping and it is attributed to Surface Enhanced Raman Scattering (SERS).

8807-13, Session 3

Well-ordered patterning of multi-functional ZnO by templated growth and self-organization technique

Romain Parize, Anna Rumyantseva, Hind Kadiri, Mathieu Tobori, Komla Nomenyo, Christophe Couteau, Anisha Gokarna, Gilles Lérondel, Univ. de Technologie Troyes (France)

Ordered arrays of 1D ZnO nanowires (NWs) are essential for applications in optoelectronic devices because of device performance improvement but they are also essential for advanced light-matter interaction control i.e. absorption and emission enhancement.

The aim of this work is to demonstrate selective, patterned growth of ZnO using low cost, easy-to-fabricate templates by the top-down and bottom-up approach. The bottom-up approach combines the fabrication of self-organized templates of functionalized polystyrene (PS) beads followed by the growth of ZnO using low temperature chemical bath deposition (CBD) method. ZnO nucleation layer is deposited on the PS beads prior to the synthesis of ZnO NWs. Formation of highly crystalline, luminescent ultra-narrow NWs with diameter lower than 10 nm are observed to be formed around the PS beads leading to a new kind of urchin-like ZnO. A second, novel, top-down approach using two-beam laser interference lithography for patterning silicon substrates is also reported. Large scale structuring of the substrate is performed using this technique. Well ordered, coalesced, crystalline nanorods of ZnO are observed to grow by the CBD technique in these well-defined arrays. These patterned templates will be further incorporated in various device applications.

8807-14, Session 3

A novel route for fabricating printable photonic devices with a high refractive index *(Invited Paper)*

Carlos Pina-Hernandes, abeam Technologies, Inc. (United States)

The nanopatterning of high refractive index optical films promises the development of novel photonic nanodevices such as optical integrated circuits, imaging sensors and solar cells. Here, we demonstrate state of the art printed photonic devices and discuss their optical performance. A novel strategy for patterning inorganic films at very high resolution

by combining inorganic synthetic chemistry and printing methods was developed. This technology allows for the direct printing of optically transparent films with unmatched resolutions over large areas.

Novel hybrid organic/inorganic printable materials were synthetized for crack free films with very high resolution patterns. Sub-10 nm resolution was achieved and defines state of the art for patterning functional films [1]. Optical properties of the printed nanostructures can be tuned over a wide range of values; a refractive index higher than 2.1 and an extinction coefficient close to zero was achieved in the visible wavelength range. The proposed approach promises to drastically simplify the fabrication of photonic devices and the development of novel nanophotonic structures, which are very difficult to achieve by conventional nanofabrication processes. A variety of photonic structures have been successfully printed into TiO2 films and their optical properties were measured.

Our technology opens an original route for fabricating novel printable photonic devices at low cost and high throughput.

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8807-15, Session 4

Titanium dioxide for nanophotonics *(Invited Paper)*

Eric Mazur, Harvard Univ. (United States)

No Abstract Available

8807-16, Session 4

UV photonic structures fabrication by top-down lithography

Komla Nomenyo, Christophe Couteau, Univ. de Technologie Troyes (France); David J. Rogers, Nanovation (France); Gilles Lérondel, Univ. de Technologie Troyes (France)

Although ultraviolet lasers and LED based on GaN are readily available, zinc oxide (ZnO) is still interesting due to its large exciton binding energy, efficient radiative recombination and simpler crystal-growth processes which are significant for lower costs ZnO-based devices. On the other hand, ZnO structuring on a nanometric scale (periodicity ≤120 nm), in order to realize photonic crystal slabs, has proved to be a critical issue that is faced up by the strong mechanical properties of ZnO, making of lithography one of the main challenges to confront for the fabrication of efficient ZnO lasers and LEDs. To date only a top-down process namely focusing ion beam, has allowed the spatial control of ZnO resonant photonic crystal (PhC).

In this work, we present PhC and microcavities fabrication by electron beam lithography (EBL) combined with inductively coupled plasma reactive ion etching (ICP-RIE). EBL combined with ICP-RIE allows for a faster structuring on larger surfaces. We will both address the EBL and ICP-RIE fabrication issues which mainly include sample charging due to the use of nonconductive substrate such as sapphire and organic and inorganic compounds formation and deposition after ZnO etching with C2F6 plasma. Resin metallization prior to EBL and O2 plasma cleaning integrated in the ICP-RIE etching process were found to be very efficient to overcome the above mentioned issues leading to ZnO PhCs and microdisks. resonant in the arrays and microdisks. Structures quality was assess through micro PL results obtained by measuring µPL of photonic crystals and microcavities.

8807-17, Session 4

Practical nanophotonic architectures for ultrafast all-optical switching

Brandon Born, Christopher M. Collier, Jonathan F. Holzman, UBC Okanagan (Canada)

The all-optical switch is the fundamental building block for optical fibre frontend systems. Operation in an all-optical format eliminates the electronic bottleneck to facilitate processing and routing at terabit-per-second data rates. The challenges of these ultrafast all-optical switching devices are addressed and overcome through a series of nanophotonic architectures.

It is shown in this work that nano-scale localization of signal and control beams can be used to enhance nonlinear beam interactions and simultaneously reduce all-optical switch recovery times. The concept of a photonic nanojet is applied first to create this nonlinear all-optical beam interaction at the intense focal region between a high refractive index microsphere and a semiconductor surface. A nano-scale plasma is preferentially photoinjected at the semiconductor surface and undergoes rapid surface recombination due to the high density of surface states. Practical all-optical switching device geometries are designed, fabricated and tested for various semiconductors, and it is found that the observed picosecond recovery times can be ten times shorter (20 ps for GaAs) than a standard bulk semiconductor switch. The process of enhanced surface recombination is then accentuated through the use of semiconductor nanoparticles. The dramatic increase in the density of surface states is found to greatly reduce the all-optical switch recovery times. A Si ultrafast all-optical switch shows a 20 ps switching time, being approximately a thousand times faster than its bulk counterpart. A SiC ultrafast all-optical switch shows a 5 ps recovery time, being approximately a million times faster than its bulk counterpart. The capabilities of these new ultrafast all-optical switches are discussed for emerging photonic systems.

8807-18, Session 4

Optical scale photonic devices using complex block copolymer morphologies

Scott W. Sides, Benjamin Cowan, Tech-X Corp. (United States)

We present a numerical method for the optimization of photonic devices created from block co-polymer (BCP) templates by coupling a code which calculates nanoscale morphologies with with a code for calculating optical properties of photonic crystals.

Making commercially viable photonic devices active at optical wavelengths is challenging due to the difficulty of controlling the structure of dielectric regions with characteristic sizes on the order of 10nm-100nm.

An attractive method for creating photonic materials with these small length scales is by using block copolymers (BCP). Complex BCP formulations have the potential to form nanoscale morphologies with efficient, solution based techniques.

Numerical self-consistent field theory (SCFT) is a method that transforms the Hamiltonian of a complex system into a field theory description, whose mean-field solution is amenable to analytic and numerical methods.

The advantage of the coarse-graining SCFT algorithm is that it enables large simulations of BCP systems within minutes or hours as opposed to classical or ab initio molecular dynamics (MD) that can take days or weeks.

Initial simulations are presented of BCP mixtures on patterned substrates using the SCFT code PolySwift++. The results of these simulations can be used to create templates for fabricating nanoscale photonic devices. We then use the data from PolySwift++ in the high-performance electromagnetic simulation code VSim to study the optical characteristics of the devices. This coupling will enable theoretical investigations of novel photonic structures not currently possible.

8807-19, Session 5

Plasmonic nanoparticle transducers studied using single-particle nonlinear optical spectroscopy *(Invited Paper)*

Kenneth L. Knappenberger, Florida State Univ. (United States)

Polarization-resolved second harmonic generation (SHG) measurements were performed on solid gold nanosphere (SGN) dimers at the single-particle level. The results indicated that single-particle SHG measurements could be used to characterize the localized electromagnetic surface fields that result from excitation of inter-particle plasmon modes. For several dimers, the polarization-resolved measurements revealed that the confined surface fields were chiral. Quantitative analysis of SHG line shapes obtained from single-particle continuous polarization variation (CPV-SHG) experiments confirmed that the chirality originated from non-zero magnetic-dipolar contributions to the SGN dimer nonlinear optical response. These findings demonstrate that plasmonic nanoparticle assemblies can function as transducers that amplify both electric and magnetic fields. Correlation of SEM images and single-particle SHG measurements obtained for several SGN dimers, as well as lithographically generated nanostructures, were used to demonstrate the structure sensitivity of the CPV-SHG method.

8807-20, Session 5

Modal analysis of LSP propagation in an integrated chain of gold nanowires

Ricardo Tellez Limon, Mickael Février, Univ. de Technologie Troyes (France); Aniello Apuzzo, Université de Technologie de Troyes (France); Rafael Salas-Montiel, Sylvain Blaize, Univ. de Technologie Troyes (France)

In recent years, it has been demonstrated that light can be propagated through a chain of metallic nanoparticles due to the Localized Surface Plasmons effect.

By making use of the Fourier Modal Method, in this work we study numerically the propagation of plasmonic Bloch waves in a periodic array of gold nanowires, and its interaction with a single-mode dielectric waveguide. When the size of the nanowires is modified, at the edge of the first Brillouin zone we clearly identify different LSP resonances involved in the wave propagation mechanism: one dipolar longitudinal for nanowires of short height, and a quadrupolar and a dipolar transversal for taller ones.

In the computed dispersion curves, it is possible to observe a match of the wave-vector, k, between the fundamental mode of a dielectric waveguide and those associated to the dipolar longitudinal and quadrupolar Bloch modes of the nanowires. Thus, when the dielectric waveguide approaches to the nanowires, a directional coupling can be achieved. On the other hand, even when the dipolar transversal Bloch mode of the nanowires is not matched with the dielectric waveguide mode, it is still possible to observe a strong interaction of the field between both structures.

The used numerical method allowed us to determine the transmission, reflection and absorption of the structure in a spectrum range from 400 nm to 1.5 µm, as well as near field maps of the electromagnetic field components.

The obtained results show that the designed structure can be used as an integrated optical sensor with a sensing efficiency which can be improved by adjusting the geometrical parameters of the metallic nanowires.

8807-21, Session 5

Matrix induced in-situ growth of crystalline Au nanoparticles for photonic applications

Christian Katzer, Friedrich-Schiller-Univ. Jena (Germany); Markus Westerhausen, Institute of Solid State Physics (Germany); Philipp Naujok, Friedrich-Schiller-Univ. Jena (Germany); Hendrik Bernhardt, Institute of Solid State Physics (Germany); Gabriele Schmidl, Wolfgang Fritzsche, Institut für Photonische Technologien e.V. (Germany); Andreas Undisz, Martin Drüe, Markus Rettenmayr, Otto Schott Institute of Materials Research (Germany); Frank Schmidl, Friedrich-Schiller-Univ. Jena (Germany)

In the past years different methods such as wet chemical synthesis where established to fabricate metal nanoparticles which can be used in biophotonic sensor devices. In order to overcome the multiple preparation steps and typical solution based problems like aggregation of particles, new in-situ methods of preparation directly on the substrate surface are highly favoured.

The authors present a novel in-situ method of fabricating gold nanoparticles by self-organization using two different matrices ($YBa_2Cu_3O_{7-\delta}$ and $SrTiO_3$) grown by a pulsed laser deposition technique. Thereby a thin gold layer self assembles into crystalline nanoparticles due to the elevated temperatures during the matrix deposition. Through a variation of the initial seed layer thickness we are able to influence the size and the distribution of the particles [1]. Furthermore by choosing a different matrix material and other deposition parameters, also the shape of the particles can be controlled [2].

As one might have to extract the nanoparticles or at least theirs tips from the surrounding matrix material to realise photonic applications we will show that this is easily possible in case of using $YBa_2Cu_3O_{7-\delta}$ as matrix material. But also when using $SrTiO_3$ one can achieve a dissolution of the surrounding matrix as we will present in first measurements. Furthermore several possibilities will be given to grow nanoparticles only at well-defined positions on the substrate. A spectral characterization of particles will be presented based on microspectroscopy.

8807-22, Session 5

Local surface plasmon polariton excitation controlled by magnetic particles

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Surface plasmon polaritons are surface electromagnetic modes propagating along metal-dielectric interfaces. This last decade, renewed interest in surface plasmon polaritons (SPP) arises from advances in nanotechnology allowing to structure surfaces at an optical subwavelength scale. Nowadays, the search for active plasmonics components has become a central issue. Active plasmonics can be achieved, for instance, by the uses of ferromagnetic materials [1]. These materials exhibit magneto-optical response, i.e., an anisotropic dielectric response controlled by a static external magnetic field. For example we have shown recently the possibility of controlling fluorescence resonance energy transfer (FRET) using a magneto-optical nanoparticle to tune the donor-acceptor interaction with the external magnetic field as an external control parameter [2].

In the present work, we study the excitation of surface plasmon polaritons on a flat metallic surface by a magneto-optical nanoparticle placed at subwavelength distance from the surface, and illuminated by a linearly polarized plane wave. We show that the directivity of plasmon excitation can be controlled with the external magnetic field. Furthermore considering the well-known LMOKE signal, for subwavelength distance above the interface, we predict an unseen intensity for this signal.

Our study is based on exact numerical simulations, using an extended coupled-dipole and Green function method that we used previously for the study of purely metallic structures [3, 4]. The numerical results are analyzed qualitatively using a perturbative approach that provides physical insight and simple rules for the design of magnetoplasmonic components.

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8807-23, Session 6

Characterization of single layer graphene using a tip-enhanced Raman spectroscopy *(Invited Paper)*

Mun Seok Jeong, Kyoung-Duck Park, Doo Jae Park, Young Hee Lee, Sungkyunkwan Univ. (Korea, Republic of)

Graphene is a promising nanophotonic material owing to its outstanding optical and electrical properties. For the synthesis of large area graphene, Chemical vapor deposition (CVD) method is widely used. However, defects on CVD grown graphene such as nucleation seeds, grain boundaries, and wrinkles are severe obstacles to fabricate high performance devices. To fabricate single layer graphene free from such defects, a thorough investigation of the physical and optical properties of those defects should be delivered in advance. We constructed an Au-tip based tip-enhanced Raman spectroscopy (TERS) system and characterized nanoscale defect structures of single layer graphene where TERS supplies a variety of multifunctional(structural, optical, and chemical) information with nanoscale resolution. The correlated information of topography, Rayleigh scattering, and Raman scattering give us interesting clues to investigate growth mechanism of nano defects of single layer graphene. We expect that our nano characterization results will be useful for controlling the quality of graphene.

8807-24, Session 6

Functional semiconductor interfaces for application in artificial photosynthesis *(Invited Paper)*

Ian Sharp, Lawrence Berkeley National Lab. (United States)

In order to sustainably meet global energy demands, it is necessary to devise new technologies capable of providing distributable power that is carbon neutral and renewable, yet price competitive. Artificial photosynthesis for direct energy conversion and storage has been proposed as a promising route for achieving these requirements. Despite the considerable effort that has been devoted to development of semiconductor photoelectrodes and solar-to-fuels catalysts, there remains a significant lack of knowledge regarding interfacial phenomena when these systems are brought into contact. Furthermore, there are few semiconductors that possess both the high efficiency and long term durability that are required for operation under harsh aqueous conditions. In order to address these challenges, we have investigated atomic layer deposited (ALD) thin films on semiconductor photoelectrodes as corrosion protection layers. Metal oxide films of a few nm thickness are capable of stabilizing semiconductors under photoelectrochemical operation and partially passivating electrically active interface states, yet simultaneously enabling efficient interfacial charge transport. However, these surfaces are not optimized for catalysing reactions associated with solar fuels generation. Therefore, we have also developed inorganic-organic systems composed of molecular hydrogen evolution catalysts covalently tethered to visible light absorbing semiconductor surfaces. Such hybrid interfaces provide models for future devices, which are expected to integrate molecular CO2 reduction catalysts for fuel formation. Surface sensitive spectroscopic methods, such as attenuated total reflection Fourier transform infrared spectroscopy and x-ray photoelectron spectroscopy are utilized to determine the specific structural and chemical properties of these interfaces at each stage of assembly. In addition, charge carrier dynamics in semiconductor photoelectrodes are investigated via transient absorption at sub-ps to ms timescales. These measurements, together with photoelectrochemical performance characterization, provide more complete understanding of the interfacial charge transfer processes and enable design improvements that are critical for achieving high efficiency solar fuel generation.

8807-25, Session 6

Theoretical research on the optical properties of magnetic fluid composed of rod-like shape nanoparticles and its micro-structure

Yong Zhao, Yu Ying, Ri-qing Lv, Northeastern Univ. (China)

In this paper, a new Molecular Dynamics model based on Rod-like magnetic nanoparticles was proposed, and it was represented in terms of translations of nanoparticles and rotations of magnetic dipole moments. Torques and forces were all considered simultaneously. In addition, the processes of cluster formation of magnetic fluid in time-varying magnetic field and stable magnetic field were compared. Different ramp rates of time-varying magnetic field were considered in the simulation analysis. For the research of optical properties of magnetic fluid, a mathematical model based on Monte Carlo (MC) method was presented and the transitivity of magnetic fluid may be computed.

In conclusion, through simulation it was found that when magnetic field was introduced in magnetic fluid, the magnetic nanoparticles suspended in carrier liquid were in translational motion and in rotational motion. In the end, the groups of magnetic nanoparticles agglomerated to form chains along the direction of magnetic field. In the simulation, the average kinetic energy of the magnetic nanoparticles decreased gradually from original state to equilibrium state. With the increasing magnetic field, the distance between magnetic columns increased and the diameter of magnetic columns decreased. In time-varying magnetic field, there were better tendency to form chains than that in constant magnetic field. The size of magnetic chains was proportional to the ramp of external magnetic field. The transitivity passed through the magnetic fluid would increase with the increasing magnetic field. The wavelength at the resonance peak of the transmission spectrum would change with different ramps of time-varying magnetic field.

8807-26, Session 6

Structural and spectroscopic characterization of glass-ceramics composed by barium titanate nanocrystals in rare earth-doped tellurite glasses

Fabio L. Oliveira, Israel Matos, Geraldo Sobral Jr., UFAL (Brazil); Elivelton Ferreira, Fabia C. Cassanjes, Gaël Y. Poirier, UNIFAL (Brazil); Jandir M. Hickmann, Márcio A. R. C. Alencar, UFAL (Brazil)

In this work, glass-ceramic samples, produced from tellurite glasses, with 99.9 (70TeO2 - 15 BaO - 15 TiO2) -0.1X2O3 (X = Eu ou Er) composition and submitted to single-step and two-steps heat treatment processes were investigated. X-ray diffraction measurements were performed and the diffraction patterns showed that, at all samples, different crystalline phases were present. Moreover, the kind of grown phases depends strongly with the employed rare-earth, heat treatment number of steps and time. For the Eu3+-doped, it was observed that samples, in which the presence of BaTiO3 was identified, showed the highest emission intensities, related to 5D1→7F1 (538 nm), 5D1→7F2 (556 nm), 5D0→ 7F0 (581 nm), 5D0→7F1 (593 nm), 5D0→7F2 (617 nm), 5D0→7F3 (654 nm) and 5D0→7F4 (702 nm) europium ions transitions, for excitation tuned at 395 nm. From absorption measurements, the oscillator strengths and the Judd-Ofelt parameters related to the electronic transitions of the Er3+-doped glass-ceramics were obtained and It was observed that these parameters were affected significantly by the presence of crystalline phases. Relatively intense infrared to green and red frequency upconversion was also observed for the Er3+-doped samples, when excited at 800 nm. Exploiting this green luminescence, we also verified that this material could be employed for optical temperature sensing, with a good sensitivity. Our results indicate that this structured material is a promising candidate for luminescent applications.

8807-27, Session 6

Nanoscale quantum-dot supercrystals

Anvar S. Baimuratov, Vadim K. Turkov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Ivan D. Rukhlenko, Monash Univ. (Australia); Alexander V. Baranov, Anatoly V. Fedorov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

We develop a theory of two-dimensional and three-dimensional supercrystals made of periodically arranged semiconductor quantum dots. The theory allows one to calculate the energy spectra and wavefunctions of the supercrystals' collective excitations, which are similar to the excitons in molecular crystals. We illustrate the developed theory by the example of two-dimensional supercrystals and the four-band model of the quantum dots' electronic subsystem. In this case, the supercrystal's energy spectrum can be found analytically for the five types of the Bravias lattices. Using analytical expressions for the energy spectra of supercrystals with different symmetries, we analyze the possibility of engineering their band structure. The engineering is possible owing to the multiple degrees of freedom associated with the changes in symmetry of the periodic lattice, variations in properties of the quantum dots or their environment, and alterations of the unit cell. We demonstrate that the variation of the supercrystal parameters enables an unprecedented control over the optical properties of the quantum-dot supercrystals and thus paves a way towards the development of new nanophotonics materials.

8808-1, Session 1

Light trapping and solar energy harvesting with photonic crystals *(Keynote Presentation)*

Sajeev John, Univ. of Toronto (Canada)

Photonic crystals are widely known for their light-trapping capabilities. This is often associated with the occurrence of a photonic band gap or other suppression in the electromagnetic density of states. An important new opportunity arises from light-trapping in the higher bands of a photonic crystal, where the electromagnetic density of states is enhanced rather than suppressed. This enables unprecedented strong absorption of sunlight in a material with weak intrinsic absorption. We describe designs of thin-film photonic crystal solar cells made of silicon, GaAs and dye-sensitized TiO2 that maximize the overall absorption of sunlight using a minimal amount of material. These crystals trap light through a parallel-to-interface negative refraction (PIR) effect and other optical resonances that occur over a broad angular and frequency range. With just one micron of silicon it possible to absorb 85% of all sunlight in the 400-1100 nm wavelength range. With 200 nm of GaAs, 95% of all available sunlight can be absorbed. Both of these exceed the Lambertian statistical ray trapping 4n2 limit. These photonic crystals offer additional opportunities for solar spectral reshaping to rival and possibly surpass the famous Shockley-Queisser power conversion efficiency limit.

8808-2, Session 1

Energy-related applications of photonic structures *(Invited Paper)*

Kai Ming Ho, Iowa State Univ. (United States)

I will present results from our recent efforts on integrating photonic structures into organic solar cells, OLEDS and transparent electrodes for windows and displays.

8808-3, Session 1

3D photonic crystals for photon management in solar cells *(Invited Paper)*

Stefan L. Schweizer, Alexander N. Sprafke, Martin-Luther Univ. Halle-Wittenberg (Germany); Ralf B. Wehrspohn, Martin-Luther Univ. Halle-Wittenberg (Germany) and Fraunhofer-Institut für Werkstoffmechanik (Germany)

Photovoltaic systems are improving their economic efficiency continuously. To reduce costs further a significant increase of the conversion efficiency from solar to electrical energy is necessary.

A promising route to improve the conversion efficiency is to increase the absorption probability by an optical light path enhancement. We present optical concepts for light management, focusing on purely dielectric structures: the potential of 3D photonic crystals for improved light trapping. The combination of spectral and angular selectivity and diffractive effects lead to optical properties which make 3D photonic crystals attractive for photon management applications.

Placed on top of a solar cell, a 3D photonic crystal structure can act as an ultra-light trapping device. It should exhibit high transmission in the direction pointing to the sun so that the photons can reach the solar cell. In all other directions the structure should be opaque to prevent the escaping of light that was not absorbed.

We present numerical calculations and give design rules for improved 3D photonic crystal ultra-light trapping.

Inverted opals integrated between the top and the bottom cell of a tandem solar cell combine reflective and diffractive properties simultaneously in one single functional layer. We show numerically and experimentally, that an increased efficiency is expected for 3D inverted opals compared to simple thin films or Bragg stacks.

Placed on the backside of a solar cell, 3D photonic crystals allow to combine the effects of a back-side mirror and a grating with much higher flexibility than the linear combination of both.

8808-4, Session 2

Light harvesting with photonic and plasmonic crystals *(Invited Paper)*

Rana Biswas, Iowa State Univ. (United States) and Ames Lab. (United States)

Long-wavelength red and infrared photons have long absorption lengths in silicon and organic solar absorber layers. We describe photon harvesting in thin film absorber layers using photonic and plasmonic crystal structures. The traditional approach has been to use randomly roughened back reflectors in thin film silicon cells that randomize the light within the absorber layer. In the Lambertian limit, the path length of photons is enhanced by the 4n2 factor.

Periodic photonic and plasmonic crystal back reflectors in conformal thin film solar cells show extraordinary broad band light harvesting. These photonic structures i) strongly diffract photons leading to waveguide resonances within the absorber layer and ii) generate large surface-plasmon field enhancements at the semiconductor metal interface. Waveguided and surface plasmon modes are coupled in these systems. These lead to enhanced absorption approaching the Lambertian limit with broadband solar absorption enhancement, exceeds 50% in a 1 micron thick nanocrystalline-Si layer[1], and 40% in organic layers. A rigorous scattering matrix approach is utilized for the simulations. The highest enhancements are obtained with an array of tapered nanocones and a conformal solar cell architecture. Experimental measurements on thin Si cells, demonstrate superior performance of the periodically patterned solar architectures than the randomly roughened one. Sources of losses and obstacles to achieving or exceeding the Lambertian limit will be discussed.

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8808-5, Session 2

Simple cubic photonic crystal for light bending and for maximizing solar absorption *(Invited Paper)*

Shawn-Yu Lin, Ping Kuang, Rensselaer Polytechnic Institute (United States); Alexei Deinega, Univ. of Toronto (Canada); Mei-Li Hsieh, National Chiao Tung Univ. (Taiwan); Sajeev John, Univ. of Toronto (Canada)

Three-dimensional (3D) photonic-crystals possess photonic bandgaps that prohibit the propagation of light in certain wavelength range in all three directions. It is also of great interest for utilizing photonic crystals for photon management and visible light trapping. A recent theoretical study showed that 3D photonic-crystals could also greatly enhance the light trapping and absorption in thin film photonic crystals due to strong resonances by parallel-interface-refraction (PIR). Here, we report on a four-layer simple cubic woodpile photonic-crystal structure successfully fabricated at nanoscales with amorphous silicon (a-Si:H) and its enhanced absorption over an unpatterned a-Si:H thin film.

8808-6, Session 2

Photon extraction: the key physics for approaching solar cell efficiency limits *(Invited Paper)*

Owen D. Miller, Massachusetts Institute of Technology (United States); Eli Yablonovitch, Lawrence Berkeley National Lab. (United States) and Univ. of California, Berkeley (United States)

Photon management is a fundamental criterion for approaching solar cell efficiency limits. Counter-intuitively, the cell should be designed for maximum extraction of photons, at open-circuit. The voltage penalty for imperfect extraction is logarithmic in the external fluorescence yield, which is highly sensitive to both intrinsic material radiative properties as well as structural non-idealities. This explains in part the substantial gap between experimental efficiency records and theoretical limits. However, it also provides a mechanism for closing the gap, as there is a substantial reward in voltage and power from small improvements in extraction. Solar cells are an exception to the rule of diminishing returns; conversely, incremental enhancements can generate significantly improved performance.

It is well understood that enhancing photon absorption improves short-circuit current and solar cell performance. Here we assert that photon extraction is equivalently important to the open-circuit voltage, the other half of the solar cell output power P=I*V. Moreover, the refractive index asymmetry between the absorber and its surroundings increases the difficulty of extraction relative to absorption, further elevating its importance. Thus external fluorescence efficiency should be a key design driver as new concepts ranging from plasmonic resonances to carrier upconversion are suggested and tested.

Recently, the single-junction solar cell efficiency record dramatically improved from 26.4% to 28.8%, with a 90 mV open-circuit voltage increase demonstrating the importance of extraction. Looking forward, photon management will play an important role in materials selection, novel surface textures and nano-structures, and ultimately in which technologies emerge with breakthrough efficiencies.

8808-7, Session 3

Meta-infrared detectors *(Invited Paper)*

Sanjay Krishna, The Univ. of New Mexico (United States)

There is an increased emphasis on obtaining detectors with enhanced functionality at the pixel level. Meta-infrared detectors in which meta materials are combined with metamaterial structures are a promising way to realize this. The infrared region is appealing due to the low metallic loss, large penetration depth of the localized field and the larger feature sizes compared to the visible region. We will discuss approaches to realize multicolor detectors using these approaches.

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8808-8, Session 3

All-semiconductor photonic-crystal route to absorption harnessing

G. Chinna R. Devarapu, Stavroula Foteinopoulou, Univ. of Exeter (United Kingdom)

We discuss a new mechanism enabling extra-ordinary absorption management, even within the Restrahlen band of a semiconductor. Our results suggest that absorption can be dramatically enhanced by appropriate manipulation of the energy velocity and its gradient at the photonic crystal interface. This recipe allowed the construction of a compact layered structure exhibiting twenty-fold absorption enhancement with respect to a homogeneous structure made of the absorptive material constituent.

8808-9, Session 3

Ultra-thin optical coatings based on strong interference effects in highly absorbing media *(Invited Paper)*

Mikhail A. Kats, Romain Blanchard, Patrice Genevet, Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

Conventional optical coatings, which consist of one or more films of dielectric materials, rely on Fabry–Perot-type interference, involving multiple optical passes through transparent layers with thicknesses of the order of the wavelength. Highly absorbing dielectrics are typically not used because usually light propagation through such media minimizes interference effects.

We show that under appropriate conditions strong interference can instead persist in ultrathin, highly absorbing films, and demonstrate a new type of optical coating comprising such a film on a metallic substrate, which selectively absorbs various frequency ranges of the incident light. These coatings rely on nontrivial phase shifts at interfaces between highly-absorbing materials, and as a result have a low sensitivity to the angle of incidence and can be as thin as 5–20 nm for visible light and down to 50 nm for the infrared.

As these wide-angle coatings can be designed to have a large degree of optical absorption within a film of deeply-subwavelength thickness, they can potentially be useful in a variety of applications from ultrathin photodetectors and solar cells to optical filters, to labeling, and even the visual arts. In this talk, we will focus on several material systems including germanium, amorphous silicon, and vanadium dioxide on various substrates and demonstrate color, anti-reflection, and dichroic coatings, perfect absorbers, among other phenomena and applications.

8808-10, Session 3

Absorption-band engineering using resonant nanostructured photonic materials *(Invited Paper)*

Koray Aydin, Northwestern Univ. (United States)

Nanophotonics, the emerging field of photon-material interactions at the nanoscale, poses many challenges and opportunities for researchers both in the basic and applied sciences. I will describe our efforts in designing, realizing and characterizing nanostructured photonic materials including metals, transparent conductive oxides and inorganic semiconductors. By shaping materials at the nanoscale, one can drastically increase absorption in and/or scattering from nanostructures that could provide significant performance enhancements in photodetection, solar energy conversion and conservation, light emission applications.

In this talk, I will discuss the research efforts for realizing broadband plasmonics absorbers enabled by nanophotonic light-trapping approaches in metal-insulator-metal resonators. By using reflective metals and transparent dielectrics, we have achieved significant absorption enhancement in the metallic parts opening routes for spectrally and spatially selective light-absorbing devices that could find use in thermophotovoltaics and hot-electron collection devices. Then, I will describe light-trapping in nanostructured inorganic silicon ultrathin films which results in drastic absorption enhancement over the entire solar spectrum and over the wide range of incident angles. This approach does not involve any plasmonic components and based solely on localized and delocalized resonances in semiconductor nanostructures. This novel resonant light absorption phenomenon in semiconductors could find use light absorption in thin-film solar cells and light extraction¬in inorganic LEDs. Finally, I will talk about our preliminary results on nanostructured transparent conductive oxide contacts, which is capable of light trapping over broad range of wavelengths. Nanostructured TCO contacts could benefit both organic and inorganic photovoltaic materials, offering significant absorption and short circuit enhancements.

8808-11, Session 4

Modeling active plasmonic response *(Invited Paper)*

Daniel Hannah, Montacer Dridi, George C. Schatz, Northwestern Univ. (United States)

This talk describes two recent projects where we have used a combination of experiments and theory to study the interaction of plasmons with excited states of organic molecules. In one project that was done with Emily Weiss, we considered the influence of ligands on the time-resolved absorption spectrum of few nm gold nanoparticles. Here we used electronic structure calculations to show that the ligands contribute significantly to the plasmonic density of states, and also influence the electron-phonon coupling strength. As a result it is possible to alter the rate of energy flow between electrons and phonons, and also the flow of energy to the surrounding solvent.

In the second project, we have collaborated with Teri Odom's group to study the time evolution of exciton populations in dye molecules that are near to plasmonic particle array structures. Here we modeled the dye excited states using a 4-level model that incorporates plasmon-enhanced fields that are obtained from FDTD calculations. We find that femtosecond pumping leads to inverted populations in the dye, and emission above an intensity threshold that is strongly coupled to lattice plasmon modes.

8808-12, Session 4

Enhancement of light extraction in silicon-rich oxide light-emitting diodes by one-dimensional photonic crystal gratings *(Invited Paper)*

Pablo A. Postigo, José M. Llorens, Instituto de Microelectrónica de Madrid (Spain); Joan Juvert, Ctr. Nacional de Microelectrónica (Spain); Alfredo González, Instituto de Microelectrónica de Madrid (Spain); Carlos Domínguez, Ctr. Nacional de Microelectrónica (Spain)

In this work we show the design, the simulation and the application of one-dimensional nanophotonic structures (photonic crystal gratings) for enhancement of light extraction in light-emitting diodes (LEDs) made of silicon-rich oxide with embedded silicon nanoparticles. The LED structure consists of a poly-silicon top layer 310 nm thick, a silicon-rich oxide layer with embedded nanoparticles 26 nm thick and the silicon substrate. The gratings are formed by grooves separated with periods ranging from 200 nm to 600 nm and widths 0.75 times the period engraved on the top layer. The height of the grooves has been varied from 460 nm to 310 nm. We have performed three dimensional finite-difference time-domain simulations to obtain the values for the internal and external quantum efficiency (EQE). The light extraction efficiency has been calculated as the light collected in the far-field within a cone of 1° around the normal and has been compared with the same structure without the nanophotonic pattern. The results show that it is possible to achieve a 10 times enhancement in the EQE for optimized gratings, as it is the case of 390 nm period and 60 nm height groove for wavelengths close to 460 nm.

8808-13, Session 4

The impact of morphology on absorption and luminescence processes in organic semiconductors *(Invited Paper)*

Jon A. Schuller, Univ. of California, Santa Barbara (United States)

Organic light-emitting and energy-harvesting materials typically self-assemble into highly ordered morphologies when processed from solution or physical vapor.

Here, we describe how structural anisotropies affect absorption and luminescence processes in organic optoelectronic materials. First, we show how light absorption in thin film organic photovoltaics can be greatly enhanced by orienting organic materials relative to plasmonic and gap-mode light trapping architectures. Subsequently, we demonstrate a novel method whereby we can resolve the orientation of luminescent excitons in layered materials. We show that the perylene derivative PTCDA exhibits luminescence from intra- and inter-molecular excitons with distinct spectra, dipole strengths, and temporal dynamics.

8808-14, Session 5

Nanolasers *(Invited Paper)*

Yeshaiahu Fainman, Univ. of California, San Diego (United States)

Dense photonic integration requires miniaturization of materials, devices and subsystems, including passive components (e.g., engineered composite metamaterials, filters, etc.) and active components (e.g., lasers, modulators, detectors). This paper discusses passive and active devices that recently have been demonstrated in our laboratory, including monolithically integrated short pulse compressor utilized with silicon on insulator material platform and design, fabrication and testing of nanolasers constructed using metal-dielectric-semiconductor resonators confined in all three dimensions.

8808-15, Session 5

How small can be a nanolaser? *(Invited Paper)*

Jacob B. Khurgin, Johns Hopkins Univ. (United States); Greg Sun, Univ. of Massachusetts Boston (United States)

In this talk we consider the prospective for development of sub-wavelength sources of coherent light involving metal-dielectric cavities and often referred to as spasers. In particular we show that being a single mode device the nanolaser does not exhibit a standard threshold behavior and one can confirm lasing only buy the line narrowing. Furthermore, we show that due to radiative time shortening caused by Purcell effect, the threshold pump power (or current) in realistic significantly sub-wavelength laser becomes prohibitively high, leaving one with two choices. The first choice is to settle on devices that are sub-wavelength in two dimensions but a few wave-lengths long in the third direction. The second choice is use incoherent plasmonic sources that are just as efficient and fast as spasers, yet can operate at realistically moderate pump powers.

8808-16, Session 5

Engineered pumping controls random lasers *(Invited Paper)*

Cefe López, Consejo Superior de Investigaciones Científicas (Spain); Marco Leonetti, Claudio Conti, Univ. degli Studi di Roma La Sapienza (Italy)

Random lasers (RL) have attracted much attention but they have been largely regarded as an academic topic with little or no technological interest. Being a system based on disorder, their performance is hard to subject to control. Their spectrum is defined by the scattering material which comprises innumerable modes of random shapes and energies filling the gain band of the lasing material. Engineering the scatterers permits tuning the broad band emission [1] into a nanometre-broad line in the intensity feedback regime.

Using a spatial light modulator (SLM) to create rays of amplified spontaneous emission in the dye bath surrounding and imbibing TiO2 nanoparticles clusters gives a large degree of additional control [2] that can select single subnanometre modes in the laser [3]. Interaction between modes allows to drive the RL between resonance or intensity feedback lasing. This allows their synchronisation by mode-locking [4]. We have observed that this interaction leads to a spreading of the energy and expansion of the modes whereby highly localized, distinct lasing modes end up covering the cluster when many modes are excited [5].

When many clusters form an ensemble two length scales are involved: that related to scattering within the lasing cluster (which is sub-micrometre) and that related to inter-cluster amplification by ASE in the dye bath. By controlling the chemistry of the solution where the clusters assemble it is possible profit from the interplay between both length scales without changing the net amount of scattering material [6].

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8808-17, Session 6

Control of light with metamaterials and plasmonic structures *(Invited Paper)*

Yuri S. Kivshar, Isabelle Staude, Manuel Decker, Dragomir N. Neshev, The Australian National Univ. (Australia)

We review our recent experimental and theoretical results on the control of light emission and propagation with magnetic and electric resonances in metamaterials and plasmonic structures. We introduce a novel concept of polarization-dependent control of spontaneous emission of quantum dots through their coupling to magnetic metamaterials, analyse effects of the lattice symmetry on the properties of metasurfaces composed of periodic, random, and quasiperiodic lattices of metaatoms, and discuss novel strategies for active control of light with optical nanoantennas. We propose a novel hybrid fabrication approach combining direct laser writing with electron-beam lithography for realizing out-of-plane plasmonic nanostructures at the nanoscale.

We believe that our results open up a new way for designing plasmonic nanostructures for emission enhancement in e.g. biosensing applications, where mostly field localisation of small spherical nanoparticles is used to detect fluorescent molecules. Since higher-order modes in small nanoparticles are completely dark and even cause photoluminescence quenching, more complex structure designs, such as the split-ring resonator in our case, make higher-order plasmonic modes accessible for photoluminescence enhancement. This ultimately results in more efficient detection of quantum emitters and molecules leading to increased sensitivity. Our results also have important consequences for the design of plasmon-enhanced single photon sources.

8808-18, Session 6

Semiconductor nanowire photoluminescence: enhanced and directional emission through leaky/guided modes and Mie resonances

Ramon Paniagua-Dominguez, Consejo Superior de Investigaciones Científicas (Spain); Grzegorz Grzela, Tommy Barten, FOM Institute for Atomic and Molecular Physics (Netherlands); Yannick Fontana, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Jaime Gómez-Rivas, FOM Institute for Atomic and Molecular Physics (Netherlands); Jose A. Sanchez-Gil, Consejo Superior de Investigaciones Científicas (Spain)

Photoluminescence from finite semiconductor nanowires have been theoretically and experimentally investigated. First, we have experimentally demonstrated the directional emission of polarized light from single semiconductor nanowires. The directionality of this emission has been directly determined with Fourier microphotoluminescence measurements of vertically oriented InP nanowires. Thus semiconductor nanowires behave as efficient optical nanoantennas [1], with emission characteristics that are not only given by the material but also by their geometry and dimensions. The theoretical analysis is based on a unified picture for infinite cylinders, including in a simple manner both the leaky/guided mode dispersion relation and the corresponding Mie extinction cross sections yielding related Mie resonances [2]. It is indeed shown that equivalent formulas yield leaky modes and Mie resonances alike. Light emission from finite nanowires is then numerically investigated in various scenarios with regard to Purcell factor enhancement and directionality; simple rules are deduced upon tuning leaky/guided mode coupling through dipole position/orientation and nanowire length, that allow us to predict their antenna-like behavior and thus to tailor photoluminescence at will [2]. We anticipate the relevance of these results for the development of nanowire photon sources with optimized efficiency and/or controlled emission by the geometry. Reciprocally, the same unified theoretical analysis is shown to yield physical insight onto enhancing light absorption at designed semiconductor nanowires through Mie resonances.

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8808-19, Session 6

Spontaneous emission enhancement via guided resonance modes in GaN nanorod-array LEDs *(Invited Paper)*

Michelle L. Povinelli, The Univ. of Southern California (United States)

We examine the role of guided-resonance modes on the emission from GaN nanorod LEDs. Finite-difference time-domain simulations are employed to model incoherent emission from InGaN quantum wells in core-shell nanorod arrays. We show that high-intensity features in the far-field emission correspond to guided-resonance modes in the photonic band structure. The spontaneous emission rate is observed to peak near the guided-resonance mode frequencies. The nanorod array dimensions can thus be tuned to produce high emission at a desired wavelength. We present a nanorod array design with a Purcell factor twenty-six times higher than an equivalent slab.

8808-20, Session 6

Calibrating (non)radiative decay constants of fluorophores and the polarizability of metamaterial scatterers via the local density of photonic states

Andrej Kwadrin, A. Femius Koenderink, FOM Institute for Atomic and Molecular Physics (Netherlands)

We demonstrate the versatility of being able to create a controlled photonic environment that manipulates the local density of photonic states (LDOS) in two experiments: Firstly, as a tool to study the properties of photon emitters and secondly, to quantify the characteristics of plasmonics and metamaterials.

As photonic environment we use a mirror and a wedge-shaped dielectric spacer defined by a single gray-tone UV-lithography step. This geometry allows to perform a Drexhage experiment – studying the total decay rate as a function of emitter-mirror separation – on a single sample. In this way, we calibrate the radiative and non-radiative decay rate as well as quantum efficiency of emitters as we report for fluorescent dyes and quantum dots.

Further, we show that the unprecedented magnetic response of a metamaterial scatterer set by the scatterer's polarizability can be rigorously quantified through its dependence on a hitherto undescribed magnetic and magnetoelectric LDOS. A change in the LDOS, by variation of the scatterer-mirror distance, will cause a linewidth change of the scatterer's frequency dependent extinction cross section. For an archetypical metamaterial building block, a split ring resonator, we find a striking difference in the extinction linewidth for different split ring orientations. In our magnetoelectric point dipole model, we explain this observation by a thorough analysis of the phase relationship between the constituent electric and magnetic dipoles.

8808-21, Session 7

Graphene interaction with light *(Invited Paper)*

Andrea C. Ferrari, Univ. of Cambridge (United Kingdom)

No Abstract Available

8808-22, Session 7

Photoconductivity mechanisms in graphene *(Invited Paper)*

Marcus Freitag, IBM Thomas J. Watson Research Ctr. (United States)

We investigate the photoresponse of biased graphene on SiO2 and find that a multitude of mechanisms play a role. In particular we consider bolometric, photovoltaic, thermoelectric, and phototransistor responses. Some of these mechanisms have opposite sign, and we show that the dominating mechanism and thus the sign of the photocurrent can be switched by applying a gate voltage to the graphene transistor. When biased close to the Dirac point, where the transport current is minimized, the photovoltaic effect dominates and the photocurrent and transport current show the same sign. When biased far from the Dirac point, the bolometric effect dominates through the temperature dependence of the mobility, and the photocurrent is reversed. By modeling the various photoresponses, we are able to extract electron and lattice temperatures upon photoexcitation, and find that the electrons stay an order of magnitude hotter than the phonons.

8808-23, Session 7

Graphene-silicon heterojunctions for tunable, versatile, weak-incidence photodetection, photometry, and imaging *(Invited Paper)*

Fangze Liu, Swastik Kar, Northeastern Univ. (United States)

In this talk, we will present the results of our recent investigations of the photodetection properties of heterojunctions of silicon with graphene in the weak-incidence detection limit. We will show how the unique optical and electronic properties of graphene, coupled with the strong absorption of photons in the visible region of silicon can be utilized in conventional and unconventional methods to reach the forefronts of on-chip photodetection. In the photodiode mode, photovoltage responsivity exceeding 10^7 V/W has been achieved, with sub-picoWatt/Hz$^{1/2}$ noise equivalent power and millisecond response-times. With contrast sensitivity exceeding 10^6 V/W, these devices can potentially distinguish materials that transmit up to 99.95% of incident light, making them attractive for imaging and spectroscopy of ultra-transparent materials. In the second mode, which is a newly developed Quantum Carrier Reinvestment (QCR) Mode, the device utilizes the ultrafast carrier dynamics in graphene vis-à-vis the slow carrier recombination rate in silicon that results in extremely high quantum gain values with photocurrent responsivities obtained as high as 10^7 A/W. Layer thickening and doping of the graphitic laminae can lead to the development of solar cells with power conversion efficiency as high as 7.5%. These architectures are highly suitable for tunable and scalable, low-power, on-chip photodetection, imaging, photometry, millisecond-switching, and on-chip ultrasensitive spectroscopy; and can be further extended to low-cost photovoltaics.

8808-24, Session 7

Cavity enhanced graphene and intersubband detectors *(Invited Paper)*

Thomas Müller, Marco Furchi, Andreas Pospischil, Alexander Benz, Technische Univ. Wien (Austria); Stefan Schwarz, Technische Univ .Wien (Austria); Hermann Detz, Karl Unterrainer, Technische Univ. Wien (Austria)

In the first part of this talk we will demonstrate that graphene – a novel two-dimensional electron system comprised of a single layer of carbon atoms – shows a surprisingly strong photocurrent response and discuss the origin of its photoconductive behavior. Based on these findings we developed several concepts for graphene-based photodetectors. One of these concepts relies on the monolithic integrating of graphene with a Fabry-Pérot microcavity. These devices benefit from the large increase of the optical field inside a resonant cavity, giving rise to increased absorption. We demonstrate that the optical absorption can be 26-fold enhanced as compared to devices without cavity. In the second part, we present the design, fabrication and characterization of a metamaterial detector based on intersubband transitions in a THz quantum-cascade laser structure. The metamaterial is used to couple normal incidence radiation resonantly to the intersubband transitions. The metamaterial is formed directly by a structured top metal contact.

8808-25, Session 7

Carbon nanotube and graphene for photonic applications *(Invited Paper)*

Shinji Yamashita, Amos Martinez, Bo Xu, The Univ. of Tokyo (Japan)

Graphene and semiconducting CNTs have fast saturable absorption (SA), which fits for the laser mode locker for fs-pulse generation. It has been known that they also have high third-order nonlinearity. We usually use the thin (~1um) layer of CNTs/ graphene on optical fiber ends. For the high power applications, we sometimes use evanescent field interaction in CNTs using CNTs/ graphene-coated D-shaped or tapered fiber, to avoid the optical damage.

We have applied the CNT-based SA in many kinds of passively mode-locked fiber lasers. We have demonstrated that these lasers can easily generate high-quality nearly transform-limited pulses, regardless of the laser configurations. It can work not only in soliton mode-locked fiber lasers, but also in more advanced mode-locked fiber lasers, such as similariton or dissipative soliton mode-locked fiber lasers.

Compared with other SAs, CNT-based SA is small, low-loss, and compatible to fibers, which is good for short-cavity fiber lasers with high repetition rate. We have succeeded in generating pulses at up to 20GHz repetition rate from a 5mm-long fiber laser.

Graphene is more attractive than CNT because of its wavelength independence. We demonstrated that the optical deposition is also possible and that the mode locking properties are quite similar to the CNT-based one. We also realized short-cavity (1cm) high-repetition-rate (10GHz) graphene-based mode-locked fiber laser.

As for the nonlinear functional devices, we succeeded in wavelength conversion of 10Gb/s NRZ signal through four-wave mixing (FWM) in the CNT-coated D-shaped or tapered fiber.

8808-26, Session 8

Plasmonic nanoparticle based nanobiosensors and nanophotodetectors *(Invited Paper)*

Ekmel Özbay, Neval A. Cinel, Bilkent Univ. (Turkey); Serkan Bütün, Northwestern Univ. (United States)

Plasmonics mainly deals with light-matter interactions in metallic nanostructures. It has gathered interest since its discovery due to the benefits it provides when compared with photonics and electronics. It owes its popularity to the tremendous number of applications it serves for. Plasmonic nanoparticles have a wide variety of applications. In this talk, we will explain how plasmonic nanoparticles can be utilized in applications such as localized surface plasmon resonance based biosensing and enhancing performance of photodetectors. In the first part, EBL fabricated plasmonic nano-disks functioning as LSPR based refractive index sensors were implemented. In the second part, the integration of nano structures with MSM photodetectors were shown to increase the coupling of more light into the device and thereby increase the responsivity and photocurrent enhancement.

8808-27, Session 8

Aluminium plasmonics

Lifei Liu, Mark W. Knight, Rice Univ. (United States); Henry O. Everitt, Duke Univ. (United States); Naomi J. Halas, Peter Nordlander, Rice Univ. (United States)

Aluminum for plasmonic nanostructures has great potential to be used in many new applications, such as access to short wavelength regions of the spectrum, complementary metal-oxide-semiconductor (CMOS) compatibility, and the possibility of low-cost, sustainable, mass-producible plasmonic materials. Here we investigate the properties of individual Al nanorod antennas with cathodoluminescence (CL).[1] This method allows us to image the local density of optical states (LDOS) of Al nanorod antennas with a spatial resolution less than 20 nm and to identify the radiative modes of these nanostructures across the visible and into the UV spectral range. The results, which are in good agreement with finite difference time domain (FDTD) simulations, lay the foundations for precise Al plasmonic nanostructure design for a variety of applications.

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8808-28, Session 8

Efficient optical trapping and manipulation of nanometer-scale particles with coaxial plasmonic apertures *(Invited Paper)*

Jennifer A. Dionne, Amr Saleh, Brian Baum, Hadiseh Alaeian, Stanford Univ. (United States)

Sculpted electromagnetic beams can serve as optical tweezers, allowing small objects to be accelerated, manipulated, or trapped with light . In this work, we theoretically and experimentally investigate plasmonic coaxial apertures as low-power optical traps for nano-sized specimens. When a particle interacts with the near field of a coaxial aperture illuminated with a linearly polarized plane wave, it experiences an optical trapping force. Unlike many prior plasmonic traps, the proposed coaxial structure traps particles at the surface of the aperture rather than inside it. Consequently, further manipulation and processing can be performed on the trapped particle.

We systematically examine this induced optical force using Maxwell stress tensor formalism and finite-difference time-domain simulations. We show that the induced trapping potential can stably trap dielectric particles smaller than 10 nm in diameter while keeping the trapping power level below 20 mW. By tapering the thickness of the coaxial dielectric channel, trapping can be extended to sub-2 nm particles. Our results also indicate that the trapped particle experiences a pulling force of the order of tens of pico-newton which can be utilized to apply localized forces on micro and nanoscale objects with nanometer precision. Experimentally, we investigate arrays of coaxial aperture traps in Au films, fabricated using focused ion beam milling. Semiconducting nanoparticles flow over the aperture and are selectively trapped at the resonant wavelengths of the aperture array. The nanoparticle fluorescence provides a direct probe of trapping of sub-10-nm particles. Our results demonstrate the potential of coaxial plasmonic apertures in enabling optical trapping and manipulation of dielectric particles ranging from single proteins to small molecules with sizes previously inaccessible.

8808-29, Session 9

Near-field thermal radiation at nanometer spacings *(Invited Paper)*

Jivtesh Garg, Poetro Sambegoro, Vazrik Chiloyan, Svetlana V. Boriskina, Massachusetts Institute of Technology (United States); Brian R. Burg, IBM Research Zurich Lab. (Switzerland); Wei-Chun Hsu, Jonathan Tong, Massachusetts Institute of Technology (United States); Keivan Esfarjani, Rutgers, The State Univ. of New Jersey (United States); Gang Chen, Massachusetts Institute of Technology (United States)

When the spacing between two surfaces is less than the dominant wavelength of thermal radiation, heat transfer between the two surfaces can significantly exceed the blackbody limit. Radiative heat transfer at small spacing is usually described by Rytov's fluctuating electrodynamics formulation, which is based on the macroscopic Maxwell equations and continuum descriptions such as dielectric functions. However, in the limit when two surfaces are in contact, heat transfer is described in terms of heat conduction and phonon transport. Today there is no unified theory that can describe the power transferred between two bodies as a function of their separation down to the zero gap contact limit. We develop an approach using lattice dynamics and the microscopic Maxwell equations to bridge the theories of conduction and radiation. Experimentally, we investigate near-field thermal radiation between two objects at extremely small separations using a sphere-plate geometry.

To measure near field thermal radiation from tens of nanometers down to direct contact, we fabricate and characterize a new type of cantilever that can decouple thermal and force signals to eliminate the parasitic deflection of the cantilever due to the force effect. Surface phonon-polariton and surface-plasmon contributions to near-field radiation heat transfer will be discussed.

This work is supported by DOE (J.G., P.S., S.B., V.C.) and UIUC MURI (W.C.H. and G. C.)

8808-30, Session 9

Quasi-coherent thermal emission from photonic crystal *(Invited Paper)*

Mei-Li Hsieh, National Chiao Tung Univ. (Taiwan); James A. Bur, Shawn-Yu Lin, Rensselaer Polytechnic Institute (United States)

We report a direct observation of a quasi-coherent thermal emission from a heated three-dimensional photonic-crystal (PhC) sample. While the sample is under Joule heating, we observed multiple oscillations in its emission interferogram and deduced a coherent-length of Lcoh ~ (20~40) um , 5-10 times longer than that of a blackbody at comparable wavelengths. The observed, relatively long coherent length is attributed to coupling of thermal emission into lossy Bloch modes that oscillate coherently over a distance determined by decay-length and the slow light nature of Bloch modes at the band edges.

8808-31, Session 9

Selective thermal emission from thin-film metasurfaces *(Invited Paper)*

William Streyer, Stephanie Law, Thomas Jacobs, Gino Rooney, Daniel M. Wasserman, Univ. of Illinois at Urbana-Champaign (United States)

The mid-infrared (mid-IR), as the spectral range where all finite temperature biological and mechanical objects emit thermal radiation, and where numerous molecular species have strong vibrational absorption resonances, is of significant importance for both security and sensing applications. The design of materials with engineered absorption resonances, which, by Kirchoff's Law, should give strongly selective emission at the design resonance upon thermal excitation, allows for the control of the spectral character of the material's thermal emission. Designed as a thin film coating, these structures can be applied to grey-body emitters to shift the grey-body thermal emission into predetermined spectral bands, altering their appearance on a thermal imaging system.

In this presentation, we will discuss two distinct selective thermal emitters. First, we investigate patterned metal antenna structures separated from a metallic groundplane by a thin dielectric layer. Here, the lateral dimensions of the patterning determine the resonant wavelength of the structure, while the thickness of the dielectric layer determines the strength of the absorption resonance. Samples with varying dielectric thickness and top metal pattern dimensions were fabricated for this work. In addition, we investigate a new class of selective thermal emitters based on thin-film, high-index lossless dielectric coatings on highly doped semiconductor designer metals. For both material systems, strongly selective thermal emission was obtained, and compared to blackbody emission at the same temperature. In addition, samples were characterized by reflection and emission spectroscopy, as a function of polarization, and emission angle. The strong spectral resonances as well as the ease of fabrication for these structures may offer a potential avenue towards thermal cloaking films and/or enhanced sensitivity mid-IR sensors.

8808-32, Session 10

Graphene plasmonics: tunability and active optical devices *(Invited Paper)*

Peter Nordlander, Rice Univ. (United States)

Graphene has emerged as an interesting material for optoelectronic applications due to its high electronic mobility and unique doping capabilities. Another interesting property of graphene structures is their remarkably narrow plasmon resonances which allows for strong coherent coupling with a nearby quantum emitter. [1] Such interactions can introduce highly nonlinear optical effects such as a plasmon blockade and saturable absorption. Due to its unique band structure, graphene can also serve as an efficient electron acceptor in active plasmonic applications. In a photodetector device, a gold nanoantenna sandwiched between two sheets can convert incident photons to hot electrons which can transfer into the graphene and be detected as an electric current. [2] Hot electrons generated from a plasmonic nanoantennas can also efficiently dope a nearby graphene sheet and create transient "optically induced electronics".[3] Finally, I will discuss some recent work on the tunability and quantum mechanical aspects of hybridized graphene plasmons in nanostructured rings and disks and rings [4]and in narrow graphene bowtie junctions.[5]

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8808-33, Session 10

Graphene optoelectronics and photonics *(Invited Paper)*

Chee Wei Wong, Tingyi Gu, Nan Shi, Shu-Wei Huang, Hao Zhou, Felice Gesuele, Obafunso Ajayi, James F. McMillan, Columbia Univ. (United States)

Our team examines the precision, quantum, ultrafast, and nonlinear measurements of photons on-chip. In this talk we describe on our studies of optical nonlinearities and carrier dynamics in graphene, a massless linear dispersion material in a purely two-dimensional Dirac fermionic structure. Measurements on the graphene-silicon hybrid photonic crystals structure demonstrate enhanced nonlinearities such as degenerate four-wave mixing for optical signal processing, time-domain regenerative oscillations, as well as optical bistability. Ultrafast spectroscopy illustrate the dramatic third-order nonlinearities in graphene, enhanced by all allowed interband optical transitions. Quasi-equilibrium carrier Coulomb scattering as well as many-body interactions will be described.

8808-34, Session 10

Controllable optical negative refraction and phase conjugation in graphene

Hayk Harutyunyan, Argonne National Lab. (United States); Ryan Beams, Univ. of Rochester (United States); Lukas Novotny, Univ. of Rochester (United States) and ETH Zurich (Switzerland)

Recent advances in the field of metamaterials added a new dimension to the science of light-matter interaction. One of the remarkable new phenomena that arise from using materials with negative permittivity and/or permeability is the negative refractive index of the materials. In his seminal work Pendry suggested that a slab of such a material, e.g. silver,

can act as a “perfect-lens” and achieve super-resolution.

However, the main obstacle for using the negative index materials in standard imaging systems is the high losses which typically limit operation to narrow frequency bands.

Alternatively, it was proposed that two phase-conjugating surfaces placed in the close proximity of an object can reverse the phase of its optical fields and form a perfect image. We demonstrate negative refraction through time-reversal using graphene layers as a phase-conjugating surface. Two pump beams at 800nm write a holographic grating on grpahene that diffracts the signal beam of the same frequency at negative angles while reversing its phase. The effect can be described as a third order nonlinear wave-mixing process, with graphene acting as a source of high optical nonlinearity. The 2-dimensional character of the sample is crucial for observation of negative refraction and realization of supper-resolution imaging lens. The measurements show a narrow resonance at the angles corresponding to negative refraction confirming that graphene acts as a time-reversal lens.

We present the first experimental demonstration of optical negative refraction through phase-conjugation.

The scheme allows all-optical control of the negative refraction without need of sophisticated and costly fabrication techniques. Choice of graphene flakes as a nonlinear material provides a robust and easy way for future fabrication of superresolution imaging devices. The linear bandstructure of graphene and its small thickness ensure virtually unlimited bandwidth and low losses of the imaging device.

8808-35, Session 10

Reconfigurable THz devices using graphene *(Invited Paper)*

Huili Xing, Univ. of Notre Dame (United States)

The terahertz (THz) frequency range has recently become one of the most dynamic areas of scientific research. However, there is still a lack of devices efficiently manipulating THz waves, such as active filters, modulators, etc. The few devices demonstrated to date have presented severe tradeoffs between insertion loss, modulation depth, and switching speed. Graphene, in the infrared/visible range, has a tunable optical absorption of 2.3%. However, its optical conductivity dramatically increases in the terahertz range, leading to an efficient modulation by electrical control. Furthermore, the two-dimensional nature of graphene enables unprecedented integration possibilities, together with its remarkable mechanical, electrical, and optical properties, promising a myriad of attractive applications.

In this talk, I will review the first demonstration of broadband graphene THz modulators as well as our recent progress on reconfigurable THz devices using graphene. Single layer graphene is capable of efficiently tuning THz transmission meanwhile introducing negligible insertion loss [APL, 113104 (2011); Nat. Comms, 3:780 (2012)]. By combining active graphene layers with other passive structures, the control over THz waves can be greatly enhanced. THz wave reflectance modulators will be discussed, exhibiting superior tradeoff than the prior art in terms of modulation depth versus insertion loss [Nano Letters 12, 4518 (2012)]. Very efficient terahertz reconfigurable metamaterial devices can be constructed employing passive metallic frequency selective surfaces (FSSs) [Optics Express 20, 28664 (2012)]. Several applications of these devices will be presented and discussed, including arrays of graphene electro-absorption modulators as electrically reconfigurable patterns for terahertz cameras [Optics Express 21, 2325 (2013)].

8808-36, Session 11

Nonlinear time reversal in a wave chaotic system *(Invited Paper)*

Matthew Frazier, Biniyam Taddese, Thomas M. Antonsen Jr., Steven M. Anlage, Univ. of Maryland, College Park (United States)

Exploiting the time-reversal invariance and reciprocal properties of the lossless wave equation enables elegantly simple solutions to complex wave-scattering problems and is embodied in the time-reversal mirror. Here we demonstrate the implementation of an electromagnetic time-reversal mirror in a wave chaotic system containing a discrete nonlinearity. We demonstrate that the time-reversed nonlinear excitations reconstruct exclusively upon the source of the nonlinearity. As an example of its utility, we demonstrate a new form of secure communication and point out other applications.

See a Synopsis of the work at http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.110.063902.

8808-38, Session 11

All-optical switching in PT-symmetric optical systems with balanced gain and loss *(Invited Paper)*

Andrey A. Sukhorukov, The Australian National Univ. (Australia); Sergey V. Suchkov, Russian Academy of Sciences (Russian Federation); Igor V. Barashenkov, Nora V. Alexeeva, Univ. of Cape Town (South Africa); Sergey V. Dmitriev, Institute for Metals Superplasticity Problems (Russian Federation); Yuri S. Kivshar, The Australian National Univ. (Australia)

Interest to the PT -symmetric systems in physics stems from Bender’s work [1], where it was shown that systems with non-Hermitian Hamiltonians can have an entirely real eigenvalue spectrum under parity-time symmetry constrain on the potential. In optics a complex refractive index can play a role of that potential [2]. Thus, optical systems with regions of balanced gain and loss can have eigenmodes which conserve their power on average. Recently PT -symmetric structures have been realized experimentally [3].

In the present work we reveal novel regimes of nonlinear wave interactions in a chain of optical PT -symmetric couplers with balanced gain and loss. The structure is governed by a system of discrete nonlinear Schrodinger equations with Kerr-type nonlinearity. We describe the interactions between different nonlinear modes: high-frequency and low-frequency solitons, soliton and breather, breather and breather [4]. We identify various scenarios of the interaction dynamics depending on model parameters and initial conditions. We also study the beam propagation in an array of optical waveguides with an embedded defect created by a pair of waveguides with gain and loss, and find that the incident high-amplitude beam can excite the mode localized at the PT – symmetric defect [5]. By exciting the localized mode of a large amplitude, it is possible to perform phase-sensitive control of beam scattering and amplification or damping of the localized mode.

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8808-39, Session 11

Modulation phase and gauge field for photons *(Invited Paper)*

Shanhui Fan, Kejie Fang, Zongfu Yu, Stanford Univ. (United States)

We show that, in photonic structures undergoing dynamic time-dependent modulation, the phase of the modulation in fact introduces a gauge potential and gauge field for photons. Controlling spatial distribution of such modulation phase then leads to a rich set of novel optical physics effects, including one-way topologically protected edge states, as well as new mechanisms for controlling the flow of eletctromagnetic waves.

8808-40, Session 12

Novel phenomena in macroscopic photonic crystals *(Invited Paper)*

Marin Soljacic, Massachusetts Institute of Technology (United States)

Photonic crystals provide superb opportunities for tailoring of the photonic density of states. This ability can in turn be explored to control radiation into far-field, enhance fluorescent light emission, as well as optimize laser emission. In order to make these phenomena useful for large macroscopic devices, large-area nano-fabrication techniques have to be successfully implemented. In this talk, I will present some of our recent theoretical and experimental progress in exploring these opportunities.

8808-41, Session 12

Photonic Floquet topological insulators *(Invited Paper)*

Mikael C. Rechtsman, Technion-Israel Institute of Technology (Israel); Julia M. Zeuner, Friedrich-Schiller-Univ. Jena (Germany); Yonatan Plotnik, Yaakov Lumer, Technion-Israel Institute of Technology (Israel); Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany); Mordechai Segev, Technion-Israel Institute of Technology (Israel); Alexander Szameit, Friedrich-Schiller-Univ. Jena (Germany)

We present the first experimental observation of Photonic Floquet Topological Insulators. Topological insulators (TIs) constitute a new state of matter: they are insulators in the bulk, but conduct electrons on the surface. In two-dimensional TIs, propagating waves are unidirectional (no backward-propagating wave), and are completely immune to scattering by defects or disorder of any kind. Photonic TIs are TIs where the propagating waves are electromagnetic, rather than electronic - in our case, visible light. Beyond their fundamental significance, photonic TIs have also been suggested for a number of applications, including highly robust optical delay lines, on-chip optical diodes, and spin-cloaked photon sources. In TIs in the solid state, topological protection is achieved by virtue of the Kramers degeneracy, which does not apply to photons. Therefore, for non-fermionic TIs, another mechanism is required to achieve topological protection. Our system is composed of an array of helical waveguides arranged in a honeycomb lattice. The helicity induces a fictitious, time-varying electric field, and the structure becomes equivalent to a “Floquet TI”. By probing the diffraction of light through the lattice, we demonstrate topologically-protected edge states, scatter-free propagation around corners as well as upon encountering defects. Our setting can potentially allow for the study of mean-field interactions (through optical nonlinearities), and the effects of highly controllable disorder.

8808-42, Session 12

Dirac cone dispersions in photonic crystals and their implications *(Invited Paper)*

Che Ting Chan, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Many unusual properties of graphene can be traced to its singular band structure near the Fermi level where two cones meet at one point. Such a dispersion is called a Dirac cone dispersion and the singular point the Dirac point. Dirac cone like dispersions are not unique to electronic graphene, but can also be found in many classical wave systems at the zone boundary as a consequence of lattice symmetry. In this talk, I will explore the consequence of having Dirac cone like dispersions at k=0. We show that Dirac cone like dispersions at k=0 can be obtained in classical wave systems using accidental degeneracy. If the photonic band dispersions originates from monopole and dipole excitations, such dispersions can be related to a double zero (zero permittivity and zero permeability) material at and near the Dirac point frequency in the sense that the system behave optically as if the refractive index is zero. From an effective medium point of view, such system has an infinite phase velocity but a finite group velocity. We will consider the extension of these ideas to from two dimensions to three dimensions and from periodic to aperiodic systems. We will also show that Dirac cone dispersions will lead to robust interface states and the origin of the robustness will discussed.

8808-43, Session 12

Anti-Hermitian plasmon coupling of gold antennas arrays for controlling light at the nanoscale *(Invited Paper)*

Shuang Zhang, The Univ. of Birmingham (United Kingdom); Xiang Zhang, Univ. of California, Berkeley (United States)

No Abstract Available

8808-44, Session 13

Ultrafast slow light control *(Invited Paper)*

Kobus Kuipers, FOM Institute for Atomic and Molecular Physics (Netherlands)

Photonic crystals are able to exert a huge control over light. Arguably one of their most interesting aspects is their ability to slowdown light. That they can achieve this feat over large bandwidths holds the promise of speeding up telecom and making it more energy efficient due to the effective enhancement of light-matter interactions.

We show that ultrafast manipulation of light is facilitated by this slowdown. Through an adiabatic control of the refractive index, we can control the properties of photonic eigenstates on (sub)-ps timescales. Light in these states can thereby be manipulated. Through changes of the refractive index in time but homogeneous in space we are able to change the frequency of the light [1]. By creating a perturbation that is not homogeneous in space we gain access to the wavevector of the slow light. By inducing frequency shifts that are wavevector dependent, we are able to tilt the photonic band structure. As a result we can spectrally compress the propagating light pulses and slow them down further [2]. With another spatial configuration of the perturbation of the eigenstates, we achieve an effective indirect photonic transition that can be used to create a delay line with which pulses can be continuously controlled in time by varying the intensity of the pump pulse [3].

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8808-45, Session 13

Engineered SOI slot photonic crystal waveguides

Charles Caer, Xavier Le Roux, Laurent Vivien, Eric Cassan, Institut d’Électronique Fondamentale (France)

Inserting a trench along a photonic crystal waveguide allows adding new functionalities to silicon photonics. These features can rely both on the high optical confinement in the slot and the properties of the infiltrating material that can overcome some limitations of silicon (e.g. nonlinear losses, indirect bandgap). The strong dispersive properties of the photonic crystal provide a higher confinement that can be managed by engineering the dispersion diagram. We propose to engineer the dispersion by structuring the shape of the slot into a comb, i.e. forming a Comb Photonic Crystal Waveguide (CPCW). These waveguides have an ultra-small nonlinear effective area which is suitable for nonlinear optical devices. Our previous works showed that such waveguides support high group index bandwidth products while they enhance the localization of light by confining the light between the etched grooves. FDTD calculations validated our design and demonstrated a high coupling efficiency by using tapers and spot-size converters. Devices fabricated by state-of-art clean room processes enable measurements of slow light when placing the CPCW in an integrated Mach-Zehnder Interferometer. High amplitude interference fringes at high group indices show that losses are low, which is confirmed by cut-back measurements, reporting losses comparable to W1 PCW at high group indices and to refractive slot waveguides at low group indices. We expect these waveguides to provide novel functionalities to silicon photonics.

8808-46, Session 13

Slow light tuning in photonic crystals *(Invited Paper)*

Toshihiko Baba, Norihiro Ishikura, Keisuke Kondo, Yokohama National Univ. (Japan)

One attractive application of slow light is tuning the delay of optical pulses. It is achieved by controlling the chirping of photonic crystal waveguides whose photonic band exhibits a flat band sandwiched by the opposite dispersion characteristics. We call the so-obtained tunable slow light dispersion-compensated (DC) slow light. In these years, we have fabricated the devices using CMOS-compatible process, demonstrated the delay tuning of sub-ps pulses with a tuning resolution over 100, and applied it to varying the demodulation rate of DQPSK receiver. The other attractive application of slow light is enhancing the nonlinearity. It is achieved by the particular design of photonic crystal waveguides, which exhibits a straight photonic band with a small slope, producing low-dispersion (LD) slow light. We have demonstrated strong two-photon absorption (TPA), self-phase modulation and four-wave mixing in Si-based devices at fiber communication wavelengths. In this presentation, we demonstrate two advanced devices that utilize both DC and LD slow light. One is the on-chip optical correlator and the other is the all-optical ultrafast delay tuning. In the former, the delay scanner based on DC slow light and nonlinear-enhanced TPA photodiode based on LD slow light were integrated. The auto-correlator action was confirmed for ps pulses. In the latter, the delay of the DC signal pulse was tuned through the intensity and timing of the LD control pulse with a maximum tuning range and response time of 10 ps. It potentially achieves the retiming of disordered pulses by using LD pulses as a clock.

8808-47, Session 14

Nonlinear optical phononics: harnessing stimulated Brillouin scattering in nonlinear nanoscale circuits *(Invited Paper)*

Benjamin J. Eggleton, The Univ. of Sydney (Australia)

I will review our recent progress in developing nanoscale optical–phononic circuits that use nonlinear optical effects to efficiently interact phonons (sound) with photons (light), creating a new paradigm in information processing. The innovation is to exploit stimulated Brillouin scattering, the strongest nonlinearity for parametric coupling of light and sound, in highly nonlinear nanoscale circuits. The new level of control over the interaction between light and sound will result in optical–phononic circuits in which light can be spectrally controlled, amplified and processed in ways currently unachievable.

8808-48, Session 14

Ultrafast nonlinear optical mirrors for all-optical applications at visible wavelengths

James J. Hsu, Canek Fuentes-Hernandez, Alfred R. Ernst, Bernard Kippelen, Georgia Institute of Technology (United States)

All-optical applications at visible wavelengths have been limited by the lack of materials and devices with a strong nonlinear optical (NLO) response. Noble metals are known to have extremely large and ultrafast NLO response at visible wavelengths but little attention has been directed at utilizing their NLO properties to develop NLO devices. In this work, we will present advances in the optimization of the linear and NLO response of metallic thin films and introduce a novel mirror structure that allows all-optical control of its reflectance at visible wavelengths.

The NLO mirror structure consists of four thin-film layers and can be engineered to display strong reflectance changes with very broad spectral and angular bandwidths across the visible spectral region. Upon being excited by a femtosecond optical pulse, an improved change of reflectance up to 25 times was observed when comparing the NLO mirror with a single Au film, having the same Au thickness, on a glass substrate. The reflectance change of the NLO mirror is ultrafast. The linear and NLO properties of these NLO mirrors can also be engineered to present narrow spectral and angular bandwidths while preserving a strong NLO response. Potential applications of these novel nonlinear optical devices will be discussed.

8808-49, Session 14

Second order nonlinear susceptibility in silicon induced by inhomogeneous strain

Jörg Schilling, Clemens Schriever, Martin-Luther-Univ. Halle-Wittenberg (Germany); Federica Bianco, Massimo Cazzanelli, Lorenzo Pavesi, Univ. degli Studi di Trento (Italy)

Today active silicon photonic components (e.g. electrooptic switches/modulators) mainly rely on refractive index changes due to charge transport in/out of the waveguide devices. However to save energy, allow higher speeds and enable advanced optical functionality (e.g. opto-optic switching, wavelength conversion,) nonlinear optical properties have to be employed in silicon photonics. Unfortunately silicon lacks a dipolar second order nonlinear susceptibility (chi(2)) due to the centrosymmetry of its diamond lattice structure. To overcome this it was recently suggested to introduce a chi(2) into silicon nanostructures applying an inhomogeneous strain which breaks the centrosymmetry locally. In the earlier realizations of this concept [1,2] always a SiNx -straining layer on top of the silicon was employed so that it was not clear if the observed chi(2) is indeed caused by the inhomogeneously strained silicon itself or by a SiNx /Si interface effect.

Here we demonstrate second harmonic generation for pump wavelengths around 2200nm on silicon strip waveguides, which were inhomogeneously strained using SiO2 cladding layers as well as differently prepared (and differently stressed) SiNx layers. The strain field was checked by XRD reciprocal space mapping and local electron diffraction. The evaluation of the measured SHG-signal of the different samples reveals that the observed chi(2) is caused by both effects – a strain induced contribution, which increases with rising strain gradients and an interface chi(2,) which is caused by the Si/SiN interface and even appears for unstrained SiN-claddings. chi(2) values in the range of 10-40pm/V were estimated for maximum strained samples. These results show that dedicated strain engineering as well as interface effects can be employed to introduce a sizeable chi(2) into silicon paving the way for second order nonlinear processes like difference frequency generation in silicon photonics.

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8808-50, Session 14

Si/chalcogenide glass hybrid waveguide design for efficient four wave mixing

Jörg Schilling, Peter W. Nolte, Christian Bohley, Martin-Luther-Univ. Halle-Wittenberg (Germany)

Although Si shows a sizeable optical third order nonlinearity, it also suffers from strong two photon absorption in the near infrared leading to a small overall nonlinear figure of merit (FOM). To overcome these limitations and be able to employ third order nonlinear processes in silicon photonics, we present here a novel design route for Silicon/chalcogenide glass hybrid slot waveguides. These hybrid waveguides allow FOM >1 and a maximum field concentration within the infiltrated material as well as a vanishing group velocity dispersion (GVD) at the same time.

Specifically, we theoretically investigated the nonlinear optical properties of slot waveguides which are infiltrated with the chalcogenide glass As2S3. Varying the waveguide width and height of the waveguides the FOM and the effective mode area was determined.

To achieve narrow band phase matching in four wave mixing processes the group velocity dispersion (GVD) must be zero. Here we propose to introduce a small periodic variation of the refractive index along the waveguide (e.g. be using the photorefractive properties of As2S3) which introduces a photonic band gap for the waveguide mode leading to band bending and a negative dispersion for the mode above the gap (second band). This negative second band dispersion compensates for the usual positive waveguide and material dispersion, so that GVD=0 can be reached for a specific frequency. Varying the periodicity of the refractive index between 300 - 400 nm allows to shift the GVD=0-frequency across the whole near infrared [1].

In conclusion the presented scheme demonstrates that the phase matching condition can be fulfilled independently from the wave guide cross section and the GVD = 0 condition can be easily tuned to the wavelength of interest allowing a flexible design of the hybrid photonic components.

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8808-51, Session 14

Resonances with the vanishing width in periodic double arrays of dielectric cylinders and their application to the second harmonic generation

Friends R. Ndangali, Amherst College (United States); Sergei V. Shabanov, Univ. of Florida (United States)

Electromagnetic bound states in the radiation continuum are similar to bound states in the radiation continuum in quantum mechanics discovered by von Neumann and Wigner. They correspond to vanishing width resonances of the scattering amplitudes. In periodic double arrays of dielectric cylinders, these states are shown to exist at specific distances between the arrays in the spectral region where one or two diffraction channels are open. When the distance between the two arrays approaches a critical value at which a bound state in the radiation continuum is formed, the near field becomes significantly amplified in specific regions of the arrays. This amplification is explained by extending the quantum mechanical Siegert state formalism to Maxwell's theory of electromagnetism. The said amplification is used to control the second harmonic generation in periodic double arrays of dielectric cylinders with a second order nonlinear susceptibility. In particular, the conversion efficiency of the incident fundamental flux into the second harmonic flux is shown to be as high as 40% at a distance between the arrays as low as half the incident radiation wavelength. Moreover, this conversion efficiency is achieved systematically however small the second order nonlinear susceptibility of the dielectric material.

8808-61, Session PWed

Novel non-linear optical properties of alumina and silica nanocomposites

Valentin A. Milichko, Vladimir P. Dzyuba, Yury N. Kulchin, Institute for Automation and Control Processes (Russian Federation)

The results of study of optical properties of nanocomposites based on dielectric matrix and Al2O3 and SiO2 nanoparticles in weak optical fields are presented. Using z scan technique, we found that nanoparticles are responsible for unique nonlinear optical phenomenon in nanocomposites: The values of portions to nanocomposite refractive index and absorption coefficient increase to maxima, and then decrease to zero when the intensity of green and violet radiation changes from 1 to 500 W/cm2. Using the spectroscopic technique, we estimated the features of electron energy structures for nanoparticles dispersed in different liquid dielectric matrices (polymethylsiloxane, water, and isopropyl alcohol) and explained the influence of the matrix permittivity value on this structure, as well as the optical properties of nanocomposites.

8808-52, Session 15

Nonclassical light sources based based on quantum dots in optical nanocavities *(Invited Paper)*

Jelena Vuckovic, Stanford Univ. (United States)

A single quantum dot coupled to an optical nanocavity or a photonic molecule can be employed to generate a stream of nonclassical light (n-photon states) with high purity and efficiency. Such states are interesting for quantum communication, metrology, high resolution quantum lithography and sensing.

We have employed a platform consisting of a single self-assembled InAs QD in a GaAs PC cavity to study quantum optics and cavity QED. In particular, we have probed the ladder of dressed states of the strongly coupled QD-cavity system and studied the regimes of photon blockade and photon induced tunneling, as well as nonclassical light generation enabled by this ladder. The regime of photon blockade enables generation of a single photon stream, while the regime of photon induced tunneling enables generation of n-photon Fock states . . To enable generation of higher purity nonclassical states of light, without the need to dramatically improve fabrication of PC cavities and QD-cavity alignment, we are studying several new approaches, including:

- QD coupled to a photonic molecule
- QD coupled to a bimodal photonic cavity
- A multi-level quantum emitter (4-levels instead of 2) coupled to a photonic cavity

8808-53, Session 15

Harnessing light with photonic nanowires: from needles to trumpets *(Invited Paper)*

Julien Claudon, Mathieu Munsch, Nitin S. Malik, Emmanuel Dupuy, Adrien Delga, Joël Bleuse, Commissariat à l'Énergie Atomique (France); Niels Gregersen, Jesper Mørk, DTU Fotonik (Denmark); Philippe Lalanne, Institut d'Optique Graduate School (France); Jean-Michel Gerard, Commissariat à l'Énergie Atomique (France)

Photonic nanowires with an out-of plane orientation have recently emerged as an appealing platform for solid-state quantum optics. These waveguides, made of a high-index material, offer a broadband and an efficient spontaneous emission control for an embedded point-like emitter [1,2]. Moreover, the collection of the guided photons can be brought close to unity with a proper engineering of the wire ends. In particular a tapering of the upper end is mandatory to achieve a directive far-field emission. Two solutions are then possible, leading to a needle-like taper [3] or to a trumpet-like one. I will show that the second strategy features key assets: i) the taper offers a clean emission into a Gaussian beam, a key asset for a wide range of situations ii) the taper performances are robust against geometrical changes, which ensures a high robustness against unavoidable fabrication imperfections [4].

As a first application in the field of quantum optics, we report the realisation of an ultra-bright single-photon source. The device, a high aspect ratio GaAs photonic trumpet containing a few InAs quantum dots, demonstrates a first-lens external efficiency of 0.75 and an external coupling efficiency to a Gaussian beam as high as 0.58.

[1] J. Bleuse et al., Phys. Rev. Lett 106, 103601 (2011)

[2] M. Munsch et al., Phys. Rev. Lett 108, 077405 (2012)

[3] J. Claudon et al., Nature Photon. 4, 174 (2010)

[4] M. Munsch et al., submitted

8808-54, Session 15

Photonic quantum technologies *(Invited Paper)*

Jeremy L. O'Brien, Univ. of Bristol (United Kingdom)

Quantum information science aims to harness uniquely quantum mechanical properties to enhance measurement, information and communication technologies, as well as to explore fundamental aspects of quantum physics. Of the various approaches to quantum computing [1], photons are particularly appealing for their low-noise properties and ease of manipulation at the single qubit level [2]. Encoding quantum information in photons is also an appealing approach to other quantum technologies [3], including quantum communication, metrology [4] and measurement [5]. We have developed an integrated waveguide approach to photonic quantum circuits for high performance, miniaturization and scalability [6–10]. We have begun to address the challenges of scaling up quantum circuits using new insights into how controlled operations can be efficiently realised [11], and demonstrated Shor's algorithm with consecutive CNOT gates [12] and the iterative phase estimation algorithm [13]. We have shown how quantum circuits can be reconfigured, using thermo-optic phase shifters to realise a highly reconfigurable quantum circuit able to perform almost any function on two photonic qubits [14], and electro-optic phase shifters in lithium niobate to rapidly manipulate the path and polarisation of telecomm wavelength single photons [15]. We have addressed miniaturisation using multimode interference coupler architectures to directly implement NxN Hadamard operations and the 'Boson sampling problem' [16], and by using high refractive index contrast materials such as SiOxNy, in which we have implemented quantum walks of correlated photons [17], and Si [18], in which we have demonstrated generation of orbital angular momentum states of light [19]. We have incorporated microfluidic channels for the delivery of samples to measure the concentration of a blood protein with entangled states of light [20]. We have begun to address the integration of superconducting single photon detectors [21] and diamond [22,23] and non-linear [24–6] single photon sources. Finally, we give an overview of recent work on fundamental aspects of quantum measurement, including a quantum version of Wheeler's delayed choice experiment [27].

8808-55, Session 15

Enhanced light-matter interactions in photonic crystal nanocavities for ultralow-power photonics *(Invited Paper)*

Masaya Notomi, NTT Basic Research Labs. (Japan)

Photonic crystals have enabled various wavelength-sized high-Q nanocavities. Such high-Q nanocavities are promising for enhancing light-matter interactions which are intrinsically weak, but it is highly important to appropriately design the structure and material to realize large enhancement. In this talk, we show how we have succeeded in observing large enhancement in nanocavities. First, we apply nanocavities to enhance emission rate in Si by combining high-Q Si nanocavities with Cu isoelectronic centers. We also show emission rate enhancement for single-photon emission at telecom wavelengths. Second, we apply nanocavities to enhance optical nonlinearity. We discuss the design strategy for nonlinear application. Finally, we discuss electro-optic device applications including lasers and photo-detectors.

8808-56, Session 15

Plasmon amplification by strong coupling in a layered structure

Aurore Castanie, Brahim Guizal, M. Antezza, Didier Felbacq, Univ. Montpellier 2 (France)

Using surface plasmon-polariton in devices, the so-called domain of "Plasmonics", poses the problem of the losses inherent to metals. Several methods have been proposed to overcome the losses, mainly by introducing active media in the vicinity of the metal. In this situation, the photon emitted by the active medium are hoped to couple the plasmonic field. However, little has been said on the microscopic aspects of the coupling between the light emitted by the active medium and the plasmon-polariton. In the present work, we propose a simple layered geometry for which we demonstrate the strong coupling between confined exciton-polariton and the plasmon-polariton. Interestingly the strong coupling induces a splitting in both the energy and the propagation constant, resulting in Rabi oscillations but also on spatial oscillations. Because of the spatial oscillations, the hybrid mode resulting from the strong coupling is geometrical concentrated in both the waveguide and the metal. This results into an automatic reduction of the spatial damping of the hybrid mode. Next, we investigate the amplification of the plasmon by adding gain into the waveguide. By following by continuity the propagation constant path in the complex plane with respect to the gain, we exhibit an inherent limitation in close connection to the situation encountered in PT-symmetric waveguides.

8808-57, Session 16

Chiral plasmonic films and nanoparticles *(Invited Paper)*

David J. Norris, ETH Zurich (Switzerland)

Plasmonic structures with chirality (or handedness) can exhibit interesting optical phenomena. This has recently been explored in patterned films, typically defined by electron beam lithography. An outstanding challenge has been to create chiral metallic nanoparticles that have only one handedness (i.e. all left-handed or all right-handed, which in molecular terminology is referred to as enantiomerically pure). Such nanoparticles can exhibit both strong circular dichroism in the visible spectral range as well as non-linear optical effects. These properties can open up applications for chiral metallic nanoparticles in sensing, separations, and optical signal processing. Here we report a novel route to enantiomerically pure chiral gold nanoparticles. Template stripping is applied to silicon wafers to prepare plasmonic films and nanoparticles with chiral shape of only one handedness. In general, template stripping utilizes the fact that coinage metals (e.g., silver, gold, and copper) will wet silicon substrates well but adhere poorly. Thus, by depositing such a metal on a patterned silicon wafer, the metal can be "stripped" off to reveal a smooth patterned film or structure that was templated by the silicon. We exploit this to develop a simple approach for obtaining chiral plasmonic structures. In particular, we demonstrate gold nanoparticles that are enantiomerically pure and have sizes controllable between 100 nm and 1 micron. Both experimental and simulated circular dichroism spectra from suspensions of the template-stripped chiral nanoparticles will be discussed.

8808-58, Session 16

Holographic fabrication of 3D optical metamaterials *(Invited Paper)*

Paul V. Braun, Univ. of Illinois at Urbana-Champaign (United States)

We have developed a genetic algorithm method for designing the diffractive optics used in phase mask lithography and performed exposures through this phase mask to realize various complex 3D structures, include optical metamaterials comprised of both dielectric and metallic constituents.

8808-59, Session 16

Synthesis of core-shell Y2O3 nanoparticles for enhanced luminescence efficiency

Ju H. Choi, Jae-Pil P. Kim, Ki H. Kim, Hye-Jeong Kim, Jeong-Ho Kim, Korea Photonics Technology Institute (Korea, Republic of)

Rare-earth (RE) ion doped core and core-shell Y2O3 phosphors have been extensively used in many applications due to the high stability and emission range and intensity. The core-shell Y2O3: (RE= Eu, Dy, Tb) nanoparticles are synthesized using a two-step process in which 100-150 nm Y2O3 core particles are synthesized using a molten salt synthesis and the shell is deposited using a sol-gel process. A shell layer, up to 10 nm thick, is controllable based on the RECl3 salt concentration. The core-shell architecture was designed for enhanced luminescence efficiency and a balanced white light appearance with long emission lifetimes. Specifically, a core-shell architecture was necessary to spatially separate the Eu3+ and Tb3+ within the phosphor to circumvent the energy transfer between them, passivate the surface quenching sites. First, the crystallinity of Y2O3 nanophosphors was characterized using X-ray analysis. RE-doped Y2O3 core nanoparticles have a good compositional homogeneity. We have also recorded absorption, fluorescence spectra and measured fluorescence lifetimes as a function of the each RE concentration in the core. After coating passive shell layer, absorption, fluorescence spectra and measured fluorescence lifetimes were compared with those from Y2O3 nanophosphor core system in order to assess the effectiveness of these core-shell phosphors. RGB combinations from each RE activator were used to produce white light. The synthesized Y2O3 nanophosphors doped with RE= Eu, Dy, Tb have high quality white light with improved emission lifetimes, suitable for application in white light LED devices.

8808-60, Session 16

Shear ordering of densely packed core-shell spheres in super viscoelastic medium for making 3D photonic crystals *(Invited Paper)*

Qibin Zhao, Andrew I. Haines, Univ. of Cambridge (United Kingdom); David R. E. Snoswell, Schlumberger Cambridge Research Ctr. (United Kingdom); Chris E. Finlayson, Aberystwyth Univ. (United Kingdom); Jeremy J. Baumberg, Univ. of Cambridge (United Kingdom)

Making photonic crystals on large scale remains highly problematic, despite their great utility for manipulating light. We have been developing routes to polymer opals, which are stretchable 3D photonic crystals comprised of densely-pakced ordered core-shell spheres. Here we demonstrate their fabrication on the kilometre-scale using a novel bottom-up bending-induced oscillatory shearing (BIOS) process.

Shearing has been widely studied yet not fully understood in both granular physics and colloidal science. Compared to most granular or colloidal systems which use a liquid inter-particle medium with low viscosity which thus has little influence, our shearing assembly works with densely-packed polymer spheres in a highly viscoelastic medium. The spheres, with a hard polystyrene core and a low Tg soft sticky polyethylacrylate shell, are pressed into thin films sandwiched between two rigid plastic foils, then sheared in the solid phase using BIOS technique. By banding the sandwiched film onto heated rollers and driving the film backward and forward repeatedly, oscillatory lateral is applied homogeneously across the whole film, and high quality flexible 3D photonic crystal films of length scale up to 1km are obtained. Optical reflection and transmission properties of the photonic crystals show the influence of processing in one direction (uni-axial BIOS) or two directions (bi-axial BIOS, 30° with respect to each other) for different numbers of passes. This is confirmed by using micro-radian x-ray scattering, which demonstrates how the in-plane and inter-plane arrangements of spheres evolves. Such polymer photonic crystals have a wide range of uses in healthcare, coatings and security applications.

8809-1, Session 1

Classical and quantum effects in graphene plasmonics *(Keynote Presentation)*

Javier García de Abajo, ICFO - Institut de Ciències Fotòniques (Spain)

We will review current results in graphene plasmonics and describe distinct features of these excitations that can only be understood from quantum theory.

8809-2, Session 1

All-color plasmonic nanolasers with ultralow thresholds *(Keynote Presentation)*

Yu-Jung Lu, National Tsing Hua Univ. (Taiwan); Jisun Kim, The Univ. of Texas at Austin (United States); Hung-Ying Chen, National Tsing Hua Univ. (Taiwan); Wen-Hao Chang, National Chiao Tung Univ. (Taiwan); Chih-Kang Shih, The Univ. of Texas at Austin (United States); Shangjr Gwo, National Tsing Hua Univ. (Taiwan)

We demonstrate that SPASER-enabled semiconductor nanolasers with 3D subwavelength sizes can emit light in the full visible spectrum (red, green, blue, etc.) by using single shape-controlled InGaN/GaN core–shell nanorods as gain media on epitaxial Ag films. The use of atomically smooth Ag films grown on Si substrates allows us to fabricate low-loss plasmonic cavities for ultralow-threshold (e.g., <10 W/cm2 for the blue nanolaser), continuous-wave (CW) nanolaser operation above liquid nitrogen temperature. Furthermore, the continuously tunable bandgap energy of the InxGa1-xN alloy makes it possible to realize all-color laser emission. Our results represent a significant step toward the realization of all-color, single-semiconductor-system nanolasers, which can become critical for display and bioimaging applications.

8809-3, Session 2

Light-induced liquid-vapor phase transitions: solar steam generation using nanoparticles *(Keynote Presentation)*

Naomi J. Halas, Rice Univ. (United States)

When an Au nanoparticle in a liquid medium is illuminated with resonant light of sufficient intensity, a nanometer scale envelope of vapor -a “nanobubble”- surrounding the particle, is formed. This is the nanoscale onset of the well-known process of liquid boiling, occurring at a single nanoparticle nucleation site, resulting from the photothermal response of the nanoparticle. We examine the steam generation process at metallic nanoparticle surfaces, and in particular at an individual metallic nanoparticle surface, in detail. Incipient nanobubble formation is observed by monitoring the plasmon resonance shift of an individual, illuminated Au nanoparticle, when its local environment changes from liquid to vapor. The temperature on the nanoparticle surface is monitored during this process, where a dramatic temperature jump is observed as the nanoscale vapor layer thermally decouples the nanoparticle from the surrounding liquid. These quantitative measurements call into question the conventional picture of macroscopic heat transfer as an appropriate description of this phenomenon. These studies provide the first direct and quantitative analysis of the evolution of light-induced steam generation by nanoparticles from the nanoscale to the macroscale, a process that is of fundamental interest for a growing number of applications. Based on both single-particle and ensemble measurements and theory, an increased understanding of the mechanism of vapor generation at liquid-immersed nanoparticle surfaces is emerging: our talk will focus on our current picture of this phenomenon as well as emerging applications based on this new solar energy harvesting approach.[1]

[1] Oara Neumann et al., ACS Nano 7, 42-49 (2013).

8809-4, Session 2

Plasmonic smart dust for probing local chemical reactions

Andreas Tittl, Xinghui Yin, Harald W. Giessen, Univ. Stuttgart (Germany); Xiang-Dong Tian, Zhong-Qun Tian, Xiamen Univ. (China); Christian Kremers, Dmitry N. Chigrin, Bergische Univ. Wuppertal (Germany); Na Liu, Max-Planck Institut für Intelligente Systeme (Germany)

Locally probing chemical reactions or catalytic processes on surfaces under realistic reaction conditions has remained one of the main challenges in materials science and heterogeneous catalysis. Where conventional surface interrogation techniques usually require high-vacuum conditions or ensemble average measurements, plasmonic nanoparticles excel in extreme light focusing and can produce highly-confined electromagnetic fields in subwavelength volumes without the need for complex near-field microscopes. Here, we demonstrate an all-optical probing technique based on plasmonic smart dust for monitoring local chemical reactions in real time. The silica shell-isolated gold nanoparticles which form the smart dust can work as strong light concentrators and optically report subtle environmental changes at their pinning sites on the probed surface during reaction processes. As a model system, we investigate the hydrogen dissociation and subsequent uptake trajectory in palladium with both “dust-on-film” and “film-on-dust” platforms. Using time-resolved single particle measurements, we demonstrate that our technique can in-situ encode chemical reaction information as optical signals for a variety of surface morphologies. The presented technique offers a unique scheme for real-time, label-free, and high-resolution probing of local reaction kinetics in a plethora of important chemical reactions on surfaces, paving the way towards the development of inexpensive and high-output reaction sensors for real-world applications.

8809-5, Session 2

Split-ball resonator

Arseniy I. Kuznetsov, A*STAR - Data Storage Institute (Singapore); Andrey E. Miroshnichenko, The Australian National Univ. (Australia); Yiguo Chen, A*STAR - Data Storage Institute (Singapore); Vignesh Viswanathan, National Univ. of Singapore (Singapore); Yuan Hsing Fu, A*STAR - Data Storage Institute (Singapore); Daniel Pickard, National Univ. of Singapore (Singapore); Boris S. Luk’yanchuk, A*STAR - Data Storage Institute (Singapore)

One of the main challenges in the field of plasmonics and metamaterials is to engineer nanostructures with strong magnetic and electric dipole resonances at visible frequencies. Getting these two resonant responses together in the same frequency range can lead to unique material properties associated with near-zero or even negative effective refractive index. Until now there were only a few experimental demonstrations of resonant magnetic response of metallic nanostructures in the red spectral region. However, strong losses inherent to plasmonic structures in the visible spectral range significantly limit possibilities to shift the magnetic resonance to shorter wavelengths. In this paper, we introduce a new concept and experimentally demonstrate a strong magnetic dipole resonance tuneable throughout the whole visible spectral range using standard plasmonic metals such as gold and silver. The key aspect is nanometer cuts fabricated inside almost perfectly spherical plasmonic nanoparticles. Such 3D spherical design allows for shifting magnetic dipole resonance down to electric dipole resonance wavelength in the visible spectral range. This results in Fano-type interference of electric and magnetic resonant modes inside the single particle. Experimentally this novel design has been realized using laser-induced transfer method to produce a perfect sphere and helium ion beam milling (HIM) to introduce a tiny cut with nanometer resolution. Due to high quality of the sphere surface controlled by strong surface tension forces during the laser transfer process and straight side walls of the cut made by HIM magnetic resonance can clearly be observed at 625 nm in gold nanoparticles. Using silver nanoparticles instead of gold can shift magnetic resonance down to blue wavelengths making it tuneable through the whole visible spectral range.

8809-6, Session 2

Femtosecond laser induced surface melting and nanojoining for plasmonic circuits

Anming Hu, Univ. of Waterloo (Canada); Guoliang Deng, Sichuan Univ. (China); Sebastien D. Courvoisier, Harvard School of Engineering and Applied Sciences (United States); Orad Reshef, Christopher C. Evans, Eric Mazur, Harvard Univ. (United States); Norman Y. Zhou, Univ. of Waterloo (Canada)

Femtosecond laser induced nonthermal processing is an emerging nanofabrication technique for delicate plasmonic devices. In this work we present a detailed investigation on the interaction between ultra-short pulses and silver nanomaterials, both experimentally and theoretically. We systematically study the laser-silver interaction at a laser fluent from 1 J/m2 to 1 MJ/m2. The optimal processing window for welding occurs at fluences of 200–450 J/m2. We investigate the size and shape effect on the interaction using finite-element time-domain (FDTD) simulation. FDTD simulation shows that a femtosecond laser pulse can induce surface melting at a few hundred J/cm2 due to the near field enhancement. The femtosecond laser-induced melting thus allows precise welding of silver nanoparticials with subnanosized gaps and silver nanowires for “T” and “X” shape circuits. These welded plasmonic circuits are successfully applied for surface enhanced Raman probes with ultrasensitive resolution, routining light propagation and cell transfection.

8809-7, Session 3

Enhanced light-matter interactions in plasmonic nanoparticle arrays *(Invited Paper)*

Teri W. Odom, Northwestern Univ. (United States)

Metal nanostructures can concentrate optical fields into highly confined, nanoscale volumes, which is important for plasmonic nanolasers, white-light generation, and enhanced non-linear optical effects. The talk will describe how arrays of strongly coupled nanoparticles and three-dimensional bowtie nanoantennas provide new routes not only to achieve these extraordinary properties but also to scale them for wide-spread applications. First, we will describe a new type of subradiant plasmon with a narrow (~5 nm) resonant linewidth that can be easily tuned by changing the height of large (> 100 nm) gold NPs arranged in a 2D array. At resonance, strong coupling between out-of-plane NP dipolar moments suppresses radiative decay, trapping light in the plane of the array and strongly localizing optical fields on each NP. Second, we will focus on NP dimers—3D bowties—that can function as optical nanoantennas. The extremely high electric field enhancements within the gap originate from the near-field interactions between the NPs. These localized fields can provide feedback for a new type of plasmonic laser based on 3D bowtie nanoparticle arrays.

8809-8, Session 3

Plasmonic antennas hybridized with dielectric waveguides

Felipe Bernal Arango, A. Femius Koenderink, FOM Institute for Atomic and Molecular Physics (Netherlands)

All the exciting properties of plasmonic nano-antennas can be used in even more versatile ways, if one can interrogate the antennas efficiently in integrated-photonic-circuits. We will present comprehensive experimental and theoretical evidence that single plasmon particles as well as plasmon Yagi-Uda antennas can be integrated with silicon nitride waveguide circuitry for efficient addressing of antennas through waveguides, as well as for creating unidirectional waveguide-coupled nanosources. In order to usefully apply the combination of plasmonic antennas and integrated dielectric waveguides it is imperative to quantify how strongly the antenna scatters waveguide modes, and conversely how the waveguide affects the antenna resonance frequency and scattering efficiency. We have realized a supercontinuum laser waveguide end-fire set up integrated with confocal and Fourier microscopy to on the one hand quantify the scattering of antennas addressed through single mode waveguides, and conversely to quantify the efficiency with which antennas can couple light into the waveguide mode. On basis of our measurements of how single objects scatter when placed on waveguides, we have successfully designed and realized waveguide integrated Yagi-Uda plasmon array antennas. We demonstrate wavelength controlled waveguide-addressable hot-spots, waveguide addressable beaming, as well as the converse, i.e., efficient unidirectional incoupling of far field radiation into the waveguide. We predict that this system allows single photon sources with beta-factors above 80%, which can be further improved by material optimization. These measurements together with simulations demonstrate that this system is ideal as a platform for plasmon quantum optics schemes as well as for fluorescence lab-on-chip applications.

8809-9, Session 3

Nanoplasmonic Fano resonances: choosing the best regime

Benjamin Gallinet, Ctr. Suisse d’Electronique et de Microtechnique SA (Switzerland)

Plasmonic modes with long radiative lifetimes combine strong nanoscale light confinement with a narrow spectral line width carrying the signature of Fano resonances, making them very promising for nanophotonic applications such as sensing, lasing, and switching. Their coupling to incident radiation, also known as radiance, determines their optical properties and optimal use in applications. An analytical model for Fano-resonant systems including non-radiative losses is introduced. It is theoretically and experimentally demonstrated that the radiance of a plasmonic mode can be classified into three different regimes. In the weak coupling regime, the line shape exhibits remarkable sensitivity to the dielectric environment. It is shown that geometrical displacements and deformations at the Ångström scale can be detected optically by measuring the radiance. In the intermediate regime, the electromagnetic energy stored in the mode is maximal, with large electric field enhancements that can be exploited in surface enhanced spectroscopy applications. In the strong coupling regime, the interaction can result in hybridized modes with tunable energies. Finally, the usage of Fano-resonant systems as biochemical sensors is discussed. It is shown that reducing Ohmic losses is the key to decreasing the limit of detection. A figure of merit including the sensitivity, spectral resolution and contrast of the Fano resonance is derived from the analytical model. A general understanding of Fano–resonant plasmonic systems emerges from this study, which should ultimately lead to optimized applications in switching and optical communications, biological and chemical sensing based on this phenomenon.

8809-10, Session 4

Passive and active tuning of optically resonant nanostructures *(Invited Paper)*

Mark Brongersma, Geballe Lab. for Advanced Materials (GLAM) (United States)

Optically resonant plasmonic and high index dielectric nanostructures form the basis of nanophotonic devices and circuits. There is a long history of spectrally tuning their optical resonances by changing the size, shape, and dielectric environment of these nanostructures. In this presentation, I will discuss ways in which these resonances can be tuned passively by electrical doping and anneal treatments as well as actively by electrical gating.

8809-11, Session 4

Nanoscale chemical imaging of plasmonic hot-spots and dark modes using photo-thermal induced resonance technique

Basudev Lahiri, Glen E. Holland, Vladimir A. Aksyuk, Andrea Centrone, National Institute of Standards and Technology (United States)

Nanomaterials are new material that has special properties owing to their nanoscale morphological features. In order to optimize the performance of nanomaterials for their potential application in number of fields such as energy harvesting, therapeutics, electronics, biology etc. it is of paramount importance that their structure-property relationship is defined clearly.

Although, the present high resolution imaging techniques (SEM, TEM etc.) provides detailed structural information at nanoscale level, the information on chemical composition of nanomaterials are obtained over a very large scale [typically at 3-10μm scale for FTIR], thereby providing an average information over large number of heterogeneous nano-objects. The Photo-Thermal Induced Resonance (PTIR) technique circumvents these limitations by combining the high lateral resolution of Atomic Force Microscopy and the high chemical specificity of IR Spectroscopy. Using PTIR technique, one can simultaneously obtain topological, chemical (IR), thermal and mechanical properties of a sample at a nanoscale level far smaller than the diffraction limit of infrared.

PTIR has been used so far for nanoscale characterization of bacteria, polymers, living cells1,2, but so far there has been no work done on utilising PTIR technique over plasmonic structures. In this work, PTIR technique is used to image bright and dark plasmonic resonances of gold Asymmetric Split Ring Resonators (A-SRRs) with nanoscale resolution. Additionally, The PTIR technique is used to map the local infrared absorption enhancement at the nanoscale, revealing absorption hot spots with local enhancement factors up to 50 times at 100 nm lateral resolution, several times better than the diffraction limit of IR light.

8809-12, Session 4

Effect of asymmetrical nanostructures on detecting the optical rotational properties of large biofilament structures

Yanjun Liu, S. Wu, A*STAR Institute of Materials Research and Engineering (Singapore); D. Popp, Institute of Molecular and Cell Biology (Singapore); Eunice S. P. Leong, A*STAR Institute of Materials Research and Engineering (Singapore); Y. L. Hor, W. K. Phua, A*STAR Institute of High Performance Computing (Singapore); K. L. Mok, Institute of Molecular and Cell Biology (Singapore); Jinghua Teng, A*STAR Institute of Materials Research and Engineering (Singapore); R. Robinson, Institute of Molecular and Cell Biology (Singapore); E. P. Li, Eng Huat Khoo, A*STAR Institute of High Performance Computing (Singapore)

In this abstract, the effects of tapered asymmetrical gammadion on the field enhancement and sensitivity detection of biomolecular structures is presented. The asymmetrical structure is made up of gold material on a glass structure. The designs are then fabricated using e-beam lithography. The chirality of the array is first determined by measuring the circular dichroism (CD) spectrum using a polarimeter. Three modes, arising from Bloch periodic theory and surface resonance mode are observed. Then each asymmetrical gammadion structure is tapered at the arms. Tapering fraction, which define the ratio of tapered end to the untapered end is used for defining the new structure designs. The CD spectra are obtained for tapered and untapered structures under different solutions. The spectra show that the three CD modes changes in degree amplitude and wavelength, especially for smaller tapering fractions for different solution. In addition, it is also observed that the field enhancement factor is significantly higher for the structures with tapering fraction less than 0.2. Subsequently, biomolecules, which has Alpha-helical and beta-sheet structures, are added. The biomolecules, with different chain lengths and chemical combination, produce larger wavelength shift compared to the untapered structures. This is due to the high field enhancement, concentrated around the taper end. This further encourages more interaction between the biomolecules and enhanced light field. The average wavelength shift due to molecular interaction is 17 nm, 13 nm and 12 nm for the tapered gammadion with tapering fraction of 0.1, 0.5 and 1 for the Bloch mode.

8809-13, Session 4

Addressing random metal-dielectric films by far-field control

Pierre Bondareff, Giorgio Volpe, Rémi Carminati, Sylvain Gigan, Ecole Supérieure de Physique et de Chimie Industrielles (France); Samuel Gresillon, Univ. Pierre et Marie Curie (France)

Addressing the nanoscale is obtained by dynamic control onto smaller and smaller objects. Efficient control of carefully designed nanoscale devices has been achieved in the past years, but fabrication and accessibility of the modes adressed from the far-field still represent open challenges. It has been shown recently on random dielectric media that disorder can be turned into an advantage to control light propagation. Combining metal and dielectric in a random system would allow to couple plasmon modes and to control their propagation from the far-field. Random metal-dielectric films which are particularly easy to fabricate and show interesting intrinsic behavior (intense subwavelentgh near-field features, broadband optical response) could therefore be used to achieve such far-field dynamical control of the optical near-field of a nanosystem. We propose a new experimental scheme where plasmonics modes are controlled by wavefront shaping of the incident beam with a spatial light modulator directly imaged on a random metal-dielectric film. This allow us to extract information about the extension of the modes, a key parameter for the far-field control of such films. Experimental results on the control of the propagation of surface plasmons polaritons on the surface will be presented. In particular, we will show that the filling fraction influences the efficiency of the coupling between far-field excitation and the plasmonic modes. This influence is what has been previously demonstrated in the near-field and paves the way towards far-field control of hot-spots.

8809-14, Session 4

Plasmonic interaction of 3D erected split-ring resonators *(Invited Paper)*

Wei Ting Chen, Chun Yen Liao, Yao-Wei Huang, Pin Chieh Wu, Shulin Sun, National Taiwan Univ. (Taiwan); Kuang-Yu Yang, Academia Sinica (Taiwan); Lei Zhou, Fudan Univ. (China); Guang-Yu Guo, National Taiwan Univ. (Taiwan) and National Chengchi

Univ. (Taiwan); Vassili A. Fedotov, Univ. of Southampton (United Kingdom); Nikolay I. Zheludev, Univ. of Southampton (United Kingdom) and Nanyang Technological Univ. (Singapore); Din Ping Tsai, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan)

Here, we designed and fabricated 3D SRR arrays by using double exposure e-beam lithography technique for investigating the plasmonic interaction in the case of 3D metamolecules. We have studied the plasmonic resonance of a single erected SRR structure. Subsequently, based on our prior work, we studied the plasmonic interactions in the cases of two, three and four 3D SRRs within a unit cell, and found magnetic plasmon-enhanced energy splitting, magnetic plasmon induced transparency (PIT) and toroidal dipole response, respectively. In the case of a metamolecule consisted by two 3D SRRs, the energy splitting of the metamolecule is enhanced because of magnetic dipolar interaction. The plasmon induced transparency (PIT) phenomenon that can be analogized of the electromagnetically induced transparency (EIT) are experimentally demonstrated in the metamolecule consisted by three 3D SRRs. In such 3D plasmonic metamaterial system, the PIT phenomenon was dominated by a magnetic dipole state coupled to a magnetic quadrupole state rather than the electric responses. Moreover, the toroidal resonances, the fundamental electromagnetic excitations that cannot be represented in terms of the standard multipole, are studied in the case of a metamolecule consisted by four 3D SRRs. We found that both the toroidal and magnetic resonances can be generated by the magnetic dipolar interaction between each SRRs. The toroidal dipolar response with lowered lasing threshold can be used to approach the lasing spaser owing to the fine field confinement. These researches have promising applications in the field of plasmonics, such as integrated 3D plasmonic metamaterials, plasmonic biosensor and lasing spaser.

8809-15, Session 5

Plasmonic sources and detectors for extreme interconnects *(Keynote Presentation)*

Meir Orenstein, Technion-Israel Institute of Technology (Israel)

Future intrachip optical interconnects will require ultrasmall reliable simple and fast light sources as well as nano-small detectors the later with substantial large voltage swing for a small number of absorbed quanta and very small internal noise. Plasmonic fits extremely well into this application - enhancing spontaneous light emission and light detection of these nanoelements, as well as mitigating effectively the coupling of the information carrying quanta from/to these nano-semiconductor structures. In addition to the enhancement of quantum efficiencies, plasmonic scheme enhances the response speed of the transmitter and receiver making plasmonics viable for this fast interconnect application

8809-16, Session 5

Enhancing charge separation in semiconductors through plasmon induced resonant energy transfer

Scott K. Cushing, Jiangtian Li, Alan D. Bristow, Nianqiang Wu, West Virginia Univ. (United States)

The solar energy conversion efficiency of semiconductors is limited by weak charge separation and partial spectral coverage. Localized surface plasmon resonance (LSPR) allows the energy of incident light to be localized to a sub-wavelength volume by the collective oscillation of surface electrons in metal nanostructures. It is well known that LSPR can enhance light trapping through multiple scattering processes and photoconversion efficiency by the transfer of the hot plasmonic carriers to the semiconductor. Our recent studies have discovered that LSPR can also increase the charge separation in a semiconductor by Plasmon-Induced Resonant Energy Transfer (PIRET). PIRET increases the charge separation above and below a semiconductor's band gap, even if an insulating barrier separates the metal and semiconductor. Although the coupling is known to proceed through a nonradiative mechanism, the details remain unclear.

We have combined transient absorption measurements with core shell nanoparticles to investigate the PIRET mechanism. The thickness of the SiO2 interlayer in the Au@SiO2@Cu2O nanoparticles is varied to determine the distance dependence of the nonradiative coupling. The LSPR is varied across the visible region by changing the size of the Ag core in the Ag@SiO2@Cu2O nanocubes, allowing the dependence of the energy transfer on the spectral overlap between the Cu2O and LSPR to be determined. The induced carrier density measured by transient absorption measurements are directly linked to action spectrum photocatalysis measurements, mapping out the PIRET mechanism. The results can be used to optimize PIRET for full spectrum photoconversion enhancement in semiconductors.

8809-17, Session 5

Room temperature lasing in gallium nitride-based nanorods structure

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In this work, we have demonstrated that the metal-cladded GaN NRs laser can be operated at room temperature. By use of the metal-cladded layer to form a cavity, the well-confined resonant mode was observed within the GaN NR that was theoretical realized by implemented finite element method to simulation. The simulation result including the lasing behavior compared with different GaN nanorod morphology and lasing mode in the metal-cladded GaN NRs laser, finally, discuss the metal layer benefit in this NR structure. In the experiment, the wavelength of lasing action was observed around 365 nm that have low threshold power density of 5.2 mJ/cm2 with high quality factor approximately 1500. We also demonstrate the large area GaN NRs stick on GaN template which adopted nanoimprnit lithography and KOH based solution etching technique to defined the GaN NR arrays and control the NRs dimension. Besides, to understand lasing action in metal-cladded nitride-based NR with shape concern as the cavity that have potential to realize the long wavelength GaN-based nanolaser.

8809-18, Session 5

Electric spaser in the extreme quantum limit *(Invited Paper)*

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We consider theoretically the spaser excited electrically via a nanowire with ballistic quantum conductance. We show that in the extreme quantum regime, i.e., for a single conductance-quantum nanowire, the spaser with the core made of common plasmonic metals, such as silver and gold, is fundamentally possible. For ballistic nanowires with multiple-quanta or non-quantized conductance, the performance of the spaser is enhanced in comparison with the extreme quantum limit. The electrically-pumped spaser is promising as an optical source, nanoamplifier, and digital logic device for optoelectronic information processing with speed ~100 GHz to ~10 THz.

8809-19, Session 6

Tunable polarization-controlled directional launching of surface plasmon-polaritons with polarization-invariant conversion efficiency *(Invited Paper)*

Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

The efficient generation of surface plasmon polaritons (SPPs) from light has traditionally faced challenges in the polarization sensitivity of the coupling efficiency and in the control of the directionality of SPPs. We have designed and demonstrated plasmonic couplers that direct SPPs depending on the polarization of the incident light. They are based on polarization sensitive aperture optical antennas, arranged in fishbone shaped columns defined in a gold film. In contrast to conventional plasmonic couplers, the total SPP conversion efficiency of the device is independent of polarization and the information on the polarization of the incident light is encoded in the state of the SPP field. Bidirectional as well as unidirectional launching of SPPs in opposite directions are demonstrated by near-field optical imaging, using linearly polarized and circularly polarized light of opposite handedness, respectively This coupling concept is further applied to circular metallic structures that that generate either radially convergent or divergent SSP depending on the handedness of the circularly polarized light , illustrating how such couplers can be extended to a broad range of designs and applications.

8809-20, Session 6

Long-wavelength infrared extraordinary transmission through Ga-doped ZnO films with 2D hole arrays

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Extraordinary optical transmission (EOT), or transmission greater than that predicted by conventional optics theory, through highly conductive ZnO films with sub-wavelength hole arrays is investigated in the long-wavelength infrared regime. EOT is facilitated by the excitation of surface plasmons and can be tuned utilizing the physical structure sizes; i. e. film thickness, period, hole diameter, and hole shape. Ga-doped ZnO films grown via pulsed laser deposition (PLD) are characterized by infrared ellipsometry and Hall measurements. PLD Ga-doped ZnO has been shown to have fluctuations in optical and electrical parameters based on fabrication techniques, providing a complimentary tuning means. The sub-wavelength 2D hole arrays are fabricated in the Ga-doped ZnO films via standard e-beam lithography and etching processes, with the optical transmission then being measured with a microscope coupled FTIR system. EOT through the structures is observed and compared with finite difference time-domain simulations. This highly conductive ZnO EOT structure may prove useful in novel integrated components such as tunable biosensors or surface plasmon coupling mechanisms.

8809-21, Session 6

Chirality in the interaction between plasmons, light, and vortex electron beams

Ana Asenjo-Garcia, Javier García de Abajo, Consejo Superior de Investigaciones Científicas (Spain)

We have studied the interaction of plasmonic chiral matter with both circularly polarized light and vortex electron beams. For light, we compare the calculations based upon multiple scattering theory with recent observations of circular dichroism (CD) in nanoparticles assembled using DNA origami [1]. We analyze the effect of varying distance between the particles and particle sizes as well as the influence of the material in the CD signals showing that it is possible to optimize the position of the particles to enhance the CD signal or to reverse its sign just with minor displacements.

For electrons, we predict strong dichroism in the electron energy-loss spectroscopy (EELS) signal by using electron vortex beams [2,3]. These vortex beams carry orbital angular momentum that can be exchanged in the interaction with chiral plasmons: when an electron looses energy by interacting with a chiral sample and it passes through a fork mask, different beams are diffracted (each with different orbital angular momentum), and the energy lost by the components with opposite units of angular momentum will be different. Incidentally, this method benefits from high spatial resolution of electron microscopes and might be really useful for magnetic dichroism imaging.

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8809-22, Session 6

On plasmon-polariton propagation along metallic nano-chain

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The collective wave type plasmon-polariton self-modes in the metallic (Au, Ag) nano-chain were determined and analyzed with respect to the nano-sphere size and chain-separation parameters. At some regions for parameters the undamped modes were identified when the interaction had been assumed as the near-field-zone dipole coupling. These modes were found on the rim of the stability of the linear theory, which indicates artifact of the model of near-field coupling. Inclusion of the medium- and far-field zone contributions to dipole interaction removes, however, instability and allows for fully analytical demonstration of exact quenching of irradiation losses of plasmon-polaritons in the chain to the level of only ohmic attenuation. The plasmon-polariton dispersion and the group velocity of plasmon-polariton wave packets were examined with respect to nano-sphere and chain parameters and mode polarization. Previous numerical results related to long range plasmon-polariton propagation including logarithmic divergence in transversal polarization plasmon-polariton dispersion due to far-field dipole coupling in the chain, are transparently interpreted within the analytical approach. The presented analysis verifies usefulness of widely applied simplifications in numerical investigation of plasmon-polariton propagation in discrete metallic nano-structures.

8809-23, Session 6

Plasmonic band theory *(Invited Paper)*

Shanhui Fan, Aaswath P. Raman, Wonseok Shin, Stanford Univ. (United States)

We show that by explicitly introducing the electronic degree of freedom, the understanding of modal properties in plasmonic structures can be significantly simplified. In particular, such formalism allows a rigorous proof of an upper bound of modal loss rate in plasmonic structures that depends only on materials, but not the detailed geometry.

8809-24, Session 7

Graphene nanoplasmonics *(Keynote Presentation)*

Harry A. Atwater Jr., Victor Brar, Michelle Sherrott, California Institute of Technology (United States); Min S. Jang, Seoul National Univ. (Korea, Republic of)

Single-layer graphene has been shown to have intriguing prospects as a plasmonic material, with modes having plasmon wavelengths ~20 times smaller than free space (λspp ~ λ0/20) have been observed in the 2-6 THz range, and active graphene plasmonic devices operating in that regime have been explored. However there is great interest in understanding the properties of graphene plasmons across the infrared spectrum, especially at energies exceeding the graphene optical phonon energy. We use infrared microscopy to observe the modes of tunable plasmonic graphene nanoresonator arrays as small as 15nm. We map the wave vector-dependent dispersion relations for graphene plasmons at mid-infrared energies from measurements of resonant frequency changes with nanoresonator width. By tuning resonator width and charge density, we probe graphene plasmons with λspp ≤ λ0/100 , and plasmon resonances as high as 310 meV (2500cm-1) for 15nm nanoresonators. Electromagnetic calculations suggest that the confined plasmonic modes have a local density of optical states more than 106 larger than free space, and thus could strongly increase light matter interactions at infrared energies.

8809-25, Session 7

Plasmon hybridization in graphene metamaterials

Atsushi Ishikawa, RIKEN (Japan); Takuo Tanaka, RIKEN (Japan) and Hokkaido Univ. (Japan)

Plasmonic properties of structured graphene and their coupling phenomena are investigated at terahertz (THz) frequencies. Two-dimensional (2D) plasmons in graphene have recently attracted much interest due to their unique plasmonic properties, such as strong field confinement, relatively long life times and dramatic tunability by electrostatic gating. Graphene plasmonics has been naturally explored in a 2D system, but stacking graphene structures into the third dimension is assumed to gain more functionality for the versatile plasmonic applications. In such complexes, plasmon coupling among neighboring graphene structures becomes more prominent and important, thus their underlying near-field interactions has to be addressed. Here, we study a stacked pair of graphene ribbons, which is the most fundamental coupled model system to describe the plasmon hybridization. We fabricated and characterized a pair of graphene ribbon on a heavily-doped Si substrate with nanometer-thick SiO2 gap layer between. The interaction between the graphene plasmons and their induced mirror images in the substrate forms a coupled system, mimicking a stacked pair of graphene ribbons, thereby dramatically modifies the mode profiles and resultant spectral responses. The polarization-dependent and gate-voltage-controllable magnetic plasmon resonances arising from the plasmon hybridization are demonstrated at THz frequencies. Excellent agreement between the experiment and numerical results reveals the important resonant behavior of structured graphene and their hybridized systems.

8809-26, Session 7

Enhanced gold film-coupled graphene-based plasmonic nanosensor

Thomas Maurer, Julien Proust, Jérémie Béal, Silvère Schuermans, Rana Nicolas, Univ. de Technologie Troyes (France); Edy Wijaya, Jean-Pierre Vilcot, Institut d'Electronique, de Microélectronique et de Nanotechnologie (France); Jérôme Plain, Univ. de Technologie Troyes (France); Rabah Boukherroub, Institut de Recherche Interdisciplinaire (France); Pierre-Michel Adam, Univ. de Technologie Troyes (France); Gaëtan Lévêque, Abdellatif Akjouj, Bahram Djafari-Rouhani, Univ. des Sciences et Technologies de Lille (France); Sabine Szunerits, Institut de Recherche Interdisciplinaire (France); Rana Nicolas, Univ. de Technologie Troyes (France) and Lebanese Univ. (Lebanon) and American Univ. of Beirut (Lebanon); Michel Kazan, American Univ. of Beirut (Lebanon); Ziad Herro, Lebanese Univ. (Lebanon)

Motivated by previous work showing that the LSPR behavior of metallic nanostructures on the top of a thin metal thin film is exquisitely sensitive to the spacer distance of the film-nanoparticles [1], we seek to investigate in the present work the influence of a few-layered graphene spacer film. As mentioned in most introductions of reports about graphene, the great deal of efforts around graphene comes from its "unique" electronic properties. However, as underlined by A. K. Geim, graphene cannot be reduced only to its "unique electronic properties" and it should be reminded that it is the only one-atom-thick materials [2]. Moreover, graphene has been theoretically considered as an alternative coating for gold based SPR [3].

Here, we take advantage of graphene's one-atom thickness in order to use it as the thinnest possible spacer between a gold film and gold nanoparticles. We investigate graphene-based SPR interface decorated with an ordered array of gold nanostructures. A commercial thermal release tape, which enables the mechanical transfer of a surface of 1 mm2 graphene sheet originally grown by chemical vapor deposition (CVD) on nickel-coated silicon substrate onto classical SPR interface (glass/5 nm Ti/ 50 nm Au). The graphene-modified SPR interface was in the following decorated with an ordered array of gold nanoparticles via electron beam lithography (EBL). On top of a chromium adhesion layer (d= 3 nm), gold nanoparticles of 50 nm in height, with a centre-to-centre distance of 300 nm and varying particle diameter (80 nm, 110 nm and 150 nm) were formed by EBL.

We have shown [4] that the deposition of a few-layers of graphene between a gold thin film of 50 nm and an ordered array of gold nanoparticles displays two clear resonances: the planar LSPR mode of the gold nanostructures at λ2 ≈ 770 nm and in addition a low wavelength LSPR mode at λ 1 ≈ 510 nm. This low wavelength mode is excited by the high energy branch of the gold film surface plasmon polaritrons, which is itself excited by the gold nanoparticle gratings. The importance in this low wavelength LSPR mode is linked to its low FMHW of 50 nm, which results in a Figure of Merit (FoM) of 2.8 at wavelength of 510 nm.

This FoM ranks this interface among the highly sensitive LSPR sensors with plasmon band in the visible at 500 nm. Indeed, most of the interfaces with high FoM (4-16.5) take advantage of the fact that higher sensitivities are achieved with plasmon bands in the near-infrared of the spectrum (850-1200 nm) [5,6]. Finally, this study provides a further understanding of systems based on arrays of resonant metallic nanoparticles coupled to metallic films. From a practical point of view, it opens the way to the engineering in a controlled and predictable way the spectral properties of metallic nanoparticles-based systems to reinforce their applicability especially in for sensing applications.

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8809-27, Session 7

Propagation and excitation of graphene plasmons

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Fotonik (Denmark); Ole Hansen, Technical Univ. of Denmark (Denmark); N. Asger Mortensen, Sanshui Xiao, DTU Fotonik (Denmark) and Technical Univ. of Denmark (Denmark)

Graphene has attracted considerable attention due to its unique electronic and optical properties. In this paper, we theoretically investigate the propagation of graphene plasmons in nanoribbon waveguides and experimentally observe the excitation of the graphene plasmons in a continuous graphene monolayer. Firstly, we investigate the performance of bends and splitters in graphene nanoribbon waveguides, and show that bends and splitters do not induce any additional loss provided that the nanoribbon width is sub-wavelength. We use transmission line theory to qualitatively interpret the behavior observed in our simulation. Then we theoretically investigate the nanofocusing of graphene plasmons in a tapered graphene waveguide and find out that the field near the tip is strongly enhanced and that graphene plasmons propagating toward the tip of the tapered graphene waveguide are slowed down. Lastly we experimentally demonstrate the excitation of graphene plasmons in a continuous graphene monolayer resting on a two-dimensional subwavelength silicon grating (SWSG). The silicon grating is realized by a nanosphere lithography technique (a widely used technique for fabricating low-cost wafer-scale samples) with a self-assembled nanosphere array as a template. A chemical-vapour-deposition-grown monolayer graphene on copper is then transferred onto the SWSG after chemically etching away the copper. Guided graphene plasmons excited in the graphene monolayer on the diffractive grating are observed in transmission spectrum measured at midinfrared frequencies. Numerical simulations and analytical resonance band properties are implemented to further support the experimental results.

8809-28, Session 7

Electro-optic modulator based on a metal-ferroelectric nanocomposite

Etai Rosenkrantz, Shlomi Arnon, Ben-Gurion Univ. of the Negev (Israel)

We present an innovative method for modulating light using a ferroelectric thin-film embedded with metal nanoparticles. Due to the electro-optic effect in ferroelectric PZT, changes in refractive index can be controlled by an external electric field. Consequently, the local surface plasmon resonance of embedded noble metal nanoparticles changes with the media's refractive index. As a result, their optical extinction cross-section is shifted and light passing through the film could be controlled. In other words, an external electric field could modulate light. Using Mie theory for spherical particles, we were able to find the metallic nanoparticle's diameter that generates the maximum optical contrast, at a given wavelength. In addition, to establish an accurate model, we considered the impact on plasmon resonance resulting from deformation of the nanoparticles. The deformation is caused by the piezoelectric property of the ferroelectric host material. We assumed 20 nm diameter Au or Ag nanoparticles embedded in a 1 µm thick PZT film. Simulations showed that these particles can reach an optical contrast of up to 12 dB, in the visible spectrum. In addition, deformation of particles had negligible impact on the shift in resonance frequency compared to the change in PZT refractive index. In this study we have shown that a nanocomposite comprising of nanoparticles embedded PZT thin film can perform as an optical modulator. This modulator will be able to achieve a high contrast with low power consumption.

8809-29, Session 7

Ultrafast all-optical magnetization reversal in GdFeCo films around plasmonic nanostructures

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It has recently been experimentally demonstrated that reproducible and controllable all-optical magnetization reversal in GdFeCo films can be achieved with a single ultrafast (from 40fs to 3ps) femtosecond laser pulse. While the microscopic origin of the effect is still unclear, the effect is believed to be caused by a combination of light-induced quasi-static magnetic field, with dynamic thermal effects due to laser heating.
This finding reveals great potential for ultrafast data storage through magnetic switching without the aid of an external magnetic field. It was further recently predicted that utilization of plasmonic nanostructures may provide the way to achieve fast all-optical magnetization switching with smaller/cheaper laser sources with longer pulse durations. We will present the simulations of temporal dynamics of magnetization reversal around plasmonic nanostructures with the combination of Landau Lifshitz Bloch and finite element modeling. Our modeling results predict that plasmonic nanostructures can significantly alter all-optical magnetization switching process and may help achieve a number of technologically important effects that cannot be achieved otherwise. Results of experimental studies of optical magnetization reversal in GdFeCo films around plasmonic nanostructures are also provided, verifying theoretical predictions.

8809-30, Session 8

Quantum optics with nanowires *(Invited Paper)*

Valery Zwiller, Reinier W. Heeres, Technische Univ. Delft (Netherlands)

We perform a Hong-Ou-Mandel experiment with indistinguishable plasmon pairs in an integrated quantum plasmonics experiment where superconducting single plasmon detectors are used for on-chip detection at the single plasmon level. We will discuss future possible implementations based on our all-on-chip approach where emission, propagation, interaction and detection can all be performed efficiently at the single photon level.

8809-31, Session 8

Entangling quantum emitters coupled to epsilon-near-zero structures in plasmonic waveguides near frequency cutoff

Ruzan Sokhoyan, Harry A. Atwater Jr., California Institute of Technology (United States)

Future quantum computing and communication systems are likely to exploit coherently coupled quantum emitters. In free space, dipole-dipole interactions between quantum emitters drastically diminish when the inter-emitter spacing is comparable to half a resonant wavelength. Coupling quantum emitters to plasmonic structures could dramatically increase their interaction range, due to the small mode volume characteristic to plasmonic fields. Within the framework of quantum electrodynamics, we articulate here how coupling quantum dipole emitters to a plasmonic waveguide could enable observation of quantum cooperative effects, focusing on the emitter entanglement and collective decay. We consider a single-mode plasmonic rectangular waveguide with a dielectric core and metal cladding which is known to mimic behavior of an epsilon-near-zero metamaterial at the frequency cutoff [1]. Assuming different resonant frequencies of the quantum emitters we investigate how the inter-emitter interactions are varied when approaching the cutoff frequency of the fundamental plasmonic mode supported by the waveguide. At the frequency cutoff of the considered geometry, one observes the enhancement of the local density of photonic states that results in the augmented emitter-field interactions. We calculate Purcell factor, collective decay and coupling parameters as a function of the

spatial position and resonant frequencies of the emitters. We investigate entanglement generation at the spontaneous transition of the emitters by calculating concurrence as a function of time. Finally, we analyze how the described effects change when non-identical emitters are involved.

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8809-32, Session 8

Graphene spaser

Vadym Apalkov, Mark I. Stockman, Georgia State Univ. (United States)

We predict that a graphene monolayer coupled to a multi-quantum well (quantum cascade) system can form a graphene spaser. This creates a coherent quantum generator of surface plasmons in graphene. The active element of the graphene spaser is a multi-quantum well system with a design similar to that of the gain medium of a quantum cascade laser. With realistic parameters of the multi-quantum well system, the spasing in the graphene monolayer can be achieved at a finite doping of graphene and at a surface plasmon frequency close to a typical frequency of intersubband transitions in multi-quantum well system.

8809-33, Session 8

Quantum plasmonics: electron transfer processes *(Invited Paper)*

Peter Nordlander, Rice Univ. (United States)

Plasmon energies can be tuned across the spectrum by simply changing the geometrical shape of a nanostructure. Plasmons can efficiently capture incident light and focus it to nanometer sized hotspots which can enhance electronic and vibrational excitations in nearby structures.[1] For narrow plasmonic junctions, quantum mechanical effects can play an important role: the large field induced in the junction can facilitate electron tunneling and charge transfer[2] and also lead no nonlinear optical response.[3] Another important but still relatively unexplored effect is production of hot energetic electrons which can transfer into nearby structures and induce a variety of processes. This process is a quantum mechanical effect: the decay of plasmon quanta into electron-hole pairs. I will discuss how plasmon induced hot electrons can be used in various applications: such as to induce chemical reactions in molecules physisorbed on a nanoparticle surface;[4] to inject electrons directly into the conduction band of a nearby substrate;[5] and to induce local doping of a nearby graphene sheet.[6]

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8809-34, Session 9

From individual to strongly coupled metallic nanocavities *(Invited Paper)*

Yehiam Prior, Adi Salomon, Weizmann Institute of Science (Israel); Radoslaw Kolkowski, Joseph Zyss, Ecole Normale Supérieure de Cachan (France)

Localized plasmonic modes of metallic nanoparticles may hybridize like atomic orbitals forming a molecule. However, the rapid decay of the plasmonic fields outside the metal severely limits the range of these interactions to tens of nanometers. Herein, we demonstrate very strong coupling of nanocavities in metal films, sustained by propagating surface plasmons with a range on the scale of hundreds of nanometers for the properly selected metal/wavelength combination. Such strong coupling drastically changes the symmetry of the charge distribution around the nanocavities making it amenable to probing by the highly symmetry sensitive nonlinear optical response of the medium. We show that when strongly coupled, equilateral triangular nanocavities lose their individual three-fold symmetry to adopt the lower two-fold symmetry of the coupled system (see Figure). The coupled system then responds like a single dipolar entity, and the SHG emission can be either enhanced or suppressed depending on the incoming beam polarization. While this phenomenon holds for nanocavities, it is very different for nanoparticles which do not couple at the same distances, a situation which seems not to obey Babinet's principle

8809-35, Session 9

Theory of plasmonic waves on a chain of metallic nanoparticles in a liquid crystalline host

Nicholas A. Pike, David G. Stroud, The Ohio State Univ. (United States)

We calculate the change in the dispersion relations of plasmonic waves along a chain of metallic nanoparticles when the host is a nematic or a cholesteric liquid crystal (NLC or CLC).

Since an NLC is uniaxially anisotropic, the standard quasistatic method for calculating the dispersion relations of plasmonic waves is modified in two ways: (i) the anisotropic host splits

the triply-degenerate single-particle dipolar plasmonic modes into a non-degenerate and a doubly degenerate mode; (ii) the dipole-dipole interaction between excitations on different

particles is modified by the host anisotropy. Including these modifications, we calculate the resulting dispersion relations for a metallic chain in an NLC host, with principal axis (director) parallel or perpendicular to the chain. Both the longitudinal (L) and transverse (T) dispersion relations are significantly changed. Furthermore, when the director is perpendicular to the chain, the doubly degenerate T branch is split into two non-degenerate linearly polarized branches. We treat a CLC with twist axis parallel to the chain as an NLC with director axis rotating around the chain axis with a characteristic pitch angle. In this case, the two T branches are again split, but are no longer linearly polarized. To illustrate these results, we calculate the L and T dispersion relations for both NLC and CLC and a Drude metal. The present work suggests that these plasmonic dispersion relations can be controlled using NLC or a CLC host and applying suitable external fields.

8809-36, Session 9

Resonance energy transfer in plasmonic systems *(Invited Paper)*

Tigran V. Shahbazyan, Jackson State Univ. (United States)

We discuss energy transfer between fluorophores such as dye molecules or semiconductor quantum dots placed nearby plasmonic structures. We develop a theory for energy transfer between quantum dots placed near a doped monolayer graphene and show that longitudinal plasmons can mediate highly efficient energy transfer at distances far exceeding the Forster radius. A simple analytical expression for energy transfer efficiency is derived that incorporates all the essential processes involved. Numerical calculations of the transfer efficiency performed for a pair of PbSe quantum dots separated by up to 1000 nm from each other indicate that plasmon-assisted long-range energy transfer can be

enhanced by up to a factor of 104 relative to the Forster's transfer in vacuum. We also discuss energy transfer from an ensemble of molecules deposited on top of a core-shell metal nanoparticle to an acceptor linked to its surface. We show that when thickness of dielectric shell is not very small, the energy transfer is dominated by cooperative effects. Our calculations show a significant increase of per donor transfer efficiency due to acceptor coupling to subradiant modes.

8809-37, Session 10

3D nanoantennas *(Invited Paper)*

Kobus Kuipers, FOM Institute for Atomic and Molecular Physics (Netherlands)

The unique optical properties of metals at optical frequencies enable a huge control of nanoscale light fields. Work in the past few years has shown how antenna concepts can be borrowed from the microwave regime and downscaled to the optical regime. This requires the fabrication of metallo-dielectric nanostructures. Here, I will present a new method to fabricate 3D nanoantenna structures, like ground-plane antennas. The resulting structures are so-called core-shell structures allowing a significant tailoring of their properties by varying the thickness of the shell. The 3D method allows the fabrication of nanoscale helices that exhibit optical dichroism.

8809-38, Session 10

Double quantum light emission from gold nanowires and interacting gold nanospheres

Mourad Abid, King Saud Univ. (Saudi Arabia); Mohamed Abid, King Saud Univ. (Saudi Arabia); Sophie Brasselet, Institut Fresnel (France)

Over the last two decades, metallic nanomaterials such as gold, silver and copper have attracted much more attention due to their unique electronic and optical properties compared to the "bulk" system [1]. These properties are strongly dependent on the characteristics of the metallic nanomaterials like the size, shape, environment and nature of the materials [2]. Noble metal nanomaterials present a strong absorption in the visible region coined as the collective oscillation of the conduction electrons and named surface plasmon polariton. While the linear optical processes in small metallic nanomaterials are well understood, few investigations have been carried out to understand the nonlinear optical processes involved in metallic nanomaterials [3]. In nonlinear optics, two photons of frequency are converted into one photon of frequency and arises from the quadratic susceptibility of the material. This process is consequently forbidden, under the dielectric dipole approximation in media with inversion symmetry and makes the nonlinear optical techniques, good candidates for probing interfaces and surfaces where the centrosymmetry is broken [4].

In this study, we investigated the angular resolved second harmonic emission of gold nanowires and interacting gold nanospheres. The study led to the identification of nonlocal dipole and local quadrupole emission in spherical nanomaterials depending on the size, the shape of the nanomaterial. By changing the polarization orientation in anisotropic metallic nanomaterials like nanowires or aggregates, it has been possible to select and control the mode of emission. Finally, we demonstrate the possibility to fashion the cartography of the local electric fields.

8809-39, Session 10

Tailoring the magnetoplasmonic response of ferromagnetic nanoparticles through symmetry breaking

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The interaction between magnetic materials and plasmon resonances has been extensively studied in the field of magnetoplasmonics. It was recently shown that ferromagnetic nickel nanoparticles support localized surface plasmon resonances that can be exploited to modify the magneto-optical behavior at will [1]. As such, the magnetization behavior that is measured in spectroscopic Magneto-Optical Kerr Effect (MOKE) measurements can change both in sign and magnitude depending on the excitation wavelength and its relative position with respect to the localized surface plasmon resonance (LSPR) frequency. The large phase change between both spectral sides of the LSPR and the intrinsic phase shift that the magnetization of the ferromagnetic material induces allows tuning of the magnetic response by means of the plasmon resonance. Here we show that symmetry breaking adds one more degree of freedom by modifying both the magnetic and optical behavior of the nanoparticles. We studied the magnetization behavior of round and elliptical nickel nanoparticles in longitudinal spectral MOKE, measuring along the different symmetry axes of the system. Magnetically, the system becomes bi-anisotropic as the particles have an easy- and a hard-axis, while two pronounced plasmon resonances can co-exist in the particles along both symmetry axes. We show that depending on the incident polarization, the wavelength of excitation and the spectral position of both plasmon resonances, we can tweak the sign, amplitude and coercivity of the magnetization behavior of the nanoparticles. Future applications include magnetic memories and (bio-) chemical sensing.

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8809-40, Session 10

Modeling plasmonic superlattice crystals *(Invited Paper)*

Michael B. Ross, Daniel Park, Martin G. Blaber, George C. Schatz, Northwestern Univ. (United States)

This talk summarizes several interrelated projects concerned with the optical properties of silver and gold nanoparticle superlattice crystals. Motivation for this work has come from recent work in Chad Mirkin's group[1] in which a large variety of superlattice crystal structures have been synthesized using DNA linkers. Optical measurements are only starting to be done, so the present work is aimed using theory to show what optical properties are possible for these structures. The calculations are mostly based on effective medium approximation calculations with Mie theory, FDTD and DDA used for the superlattice crystal. However we have also performed careful studies of the accuracy of the effective medium approximations through comparisons with generalized Mie theory and DDA calculations with explicit particles.

Our calculations for several micron size gold superlattice crystals show that these materials can show both plasmonic resonance behavior and whispering gallery mode resonances, with the former dominating at <600 nm and the latter at >700 nm, with a transition region in between. This leads to plasmon enhanced lensing optical properties at certain wavelengths and for certain volume fractions unusual backscattering properties.

For silver superlattice crystals we find a range of structures and wavelengths for which the real part of the dielectric function is negative, leading to metallic behavior even when the volume fraction is <10%. And even when the dielectric function is positive, there are unusual resonance shifts for rod-like crystal shapes such that longitudinal resonances can be blue of transverse resonances. Finally, for superlattices made from anisotropic particles, there are parameters which allow both negative permeability in addition to negative permittivity.

[1]Nanoparticle superlattices engineering with DNA, Robert J. Macfarlane, Byeongdu Lee, Matthew R. Jones, Nadine Harris, George C. Schatz, Chad A. Mirkin, Science 334, 204-208 (2011)

8809-41, Session 10

Hybrid optical antenna with high directivity gain

Alireza Bonakdar, Hooman Mohseni, Northwestern Univ. (United States)

Enhancing the coupling of diffraction limited propagating optical mode with the localized sub diffraction near field of electronic dipole has great impact on applications such as quantum metrology, optical quantum information, single molecule florescence spectroscopy and ultra sensitive photo detection. Optical metallic antenna as a far field to near field convertor enhances optical processes such as absorption and spontaneous emission. The main figure of merit to evaluate the role of antenna in delivery of optical energy to a quantum absorber and extracting it from a quantum emitter is the directivity gain. In spite of enhancing near field, existing metallic antennas such as Bowtie have resonant dimensions too small to collect far field power efficiently and deliver it directly toward the load which results in poor directivity gain. Unfortunately, increasing the metallic antenna size cannot be a solution due to elevation of ohmic loss. Here, we propose a hybrid antenna, which has a high directivity and very low loss, leading to a large antenna gain. In order to get benefit from optical absorption enhancement due to light confinement and avoid poor optical power collection, we combine dielectric and metallo-dielectric antennas. Dielectric antenna is designed to efficiently collect optical power from large area and illuminates the focused light toward metallo-dielectric antenna. On the other hand, metallo-dielectric antenna delivers the collected light to the detection site while enhancing the electric field by resonant cavity effect. With the same principle, we also fabricated and demonstrated a hybrid antenna on the facet of a fiber.

8809-42, Session 11

Nanostructures: from physics to bio and nanomedicine *(Keynote Presentation)*

Enzo Di Fabrizio, King Abdullah Univ. of Science and Technology (Saudi Arabia)

In the last few years, there has been a burst in the study and conceiving of new devices for the generation and manipulation of electromagnetic field at the nanoscale, where radiation-matter interaction is strongly enhanced. Several fabrication methods are now available for material preparation and nanostructuring, but only few of them can ensure the stringent design control needed for the effective and reproducible device behaviour.

We report, herein, novel processes of micro and nanofabrication techniques for several applications in different research fields, from material science to bioscience.

During the lecture it will be presented selected topics from the research activity at PSE and BESE divisions at KAUST. In particular it will be highlighted the results on single molecule detection, novel cell manipulation methods and early Cancer detection through novel methods based on miniaturization.

8809-43, Session 11

Direct measurement of bow-tie nanoantennas metal loss

Iman Hassani Nia, Omer G. Memis, Hooman Mohseni, Northwestern Univ. (United States)

The loss in optical antennas can affect their performance for their practical use in many branches of science such as biological and solar cell applications. However the big question is that how much loss is due to the joule heating in the metals. This would affect the efficiency of solar cells and is very important for single photon detection. This is also an important question for applications where high heat generation in nanoantennas is desirable, for example, payload release for cancer treatment. Recently several groups have demonstrated such temperature measurements using Raman spectroscopy and fluorescence polarization anisotropy. The latter method is more reliable with a temperature accuracy of ~0.1° C, but requires deposition of fluorescent molecules on the antenna surface. Here we present a method based on integrated micro-thermocouple and thermo-reflectance that allows temperature accuracy of about 0.02° C, as well as spatial resolution of ~500 nm. Moreover, this method does not require the addition of new materials to the nanoantenna. In this talk we present the measured heat dissipation from nanoantennas and compare them with 3D simulation results.

8809-44, Session 11

Extracting and focusing of surface plasmon polaritons inside finite asymmetric metal/insulator/metal structure at apex of optical fiber by subwavelength holes

Yasushi Oshikane, Osaka Univ. (Japan); Kensuke Murai, National Institute of Advanced Industrial Science and Technology (Japan); Motohiro Nakano, Takaya Higashi, Osaka Univ. (Japan)

We have been studied a finite asymmetric metal-insulator-metal (MIM) structure on glass plate for near-future visible light communication (VLC) system with white LED illuminations in the living space (DOI: 10.1117/12.929201). The metal layers are vacuum-evaporated thin silver (Ag) films (around 50 nm and 200 nm, respectively), and the insulator layer (around 150 nm) is composed of magnesium fluoride (MgF_2). A characteristic narrow band filtering of the MIM structure at visible region might cause a confinement of intense surface plasmon polaritions (SPPs) at specific monochromatic frequency inside a subwavelength insulator layer of the MIM structure. Central wavelength and depth of such absorption dip in flat spectral reflectance curve is controlled by changing thicknesses of both insulator and thinner metal layers. On the other hand, we have proposed a twin-hole pass-through waveguide for SPPs in thick Ag film (DOI: 10.1117/12.863587). At that time, the twin-hole converted a incoming plane light wave into a pair of channel plasmon polaritons (CPPs), and united them at rear surface of the Ag film. This research is having an eye to extract, guide, and focus the SPPs through a thicker metal layer of the MIM with FIBed subwavelength pass-through holes. The expected outcome is a creation of noble, monochromatic, and tunable fiber probe for scanning near-field optical microscopes (SNOMs) with intense white light sources. Basic experimental and FEM simulation results will be presented.

8809-45, Session 11

Nano-focusing of surface plasmons in metallic nano-structures: new developments and results *(Invited Paper)*

Dmitri K. Gramotnev, Nanophotonics Pty Ltd. (Australia)

The development of new optical technologies for probing, imaging and optical manipulation of nanoscale amounts of substances and single molecules is a major goal of modern nanophotonics. One of the ways for achieving this goal is based on nanofocusing of light, i.e., effective concentration and delivery of light energy to nanostructures into regions as small as a few nanometers. This paper will present and analyze the recent achievements in plasmon nanofocusing in metallic nanostructures. Structural optimization is also discussed, including the comparative analysis of the considered configurations and their applications. Special focus will be on the configurations with three-dimensional nanofocusing including three-dimensionally tapered structures and two-dimensionally tapered structures with diffraction-limited plasmon pre-focusing. These include tapered metal rods of different geometries, spherical dielectric tips covered in thin tapered metal film, dimples lenses formed in insulator-metal-insulator (IMI), metal-insulator-metal (MIM) and metal-insulator-insulator (MII) structures, etc. The benefits of efficient and low-loss diffraction-limited plasmon pre-focusing are combined with the subsequent plasmon nanofocusing to achieve the most efficient energy transfer to the nanoscale and minimize dissipative losses. The analysis will include the adiabatic and paraxial approximations, and will also involve rigorous numerical simulations. Applications for a new generation of nano-optical sensors, near-field imaging techniques with the resolution as good as a few nanometers, and near-field superresolution spectroscopy will also be considered.

8809-46, Session 11

Nonresonant broadband funneling of light via ultrasubwavelength channels

Ganapathi S. Subramania, Sandia National Labs. (United States); Stavroula Foteinopoulou, Univ. of Exeter (United Kingdom); Igal Brener, Sandia National Labs. (United States) and Ctr. for Integrated Nanotechnologies (United States)

Efficient control of light-matter interaction at deeply subwavelength scales is key to many photonics applications such as detectors, sensors and novel light sources. Enhancing and funneling light efficiently through nanoscale channels can dramatically improve the performance of such devices by making them compact and more efficient. Currently, this is accomplished by utilizing the extraordinary optical transmission phenomenon wherein structural surface plasmon resonances are excited in perforated nanostructured metal films. As a result the phenomenon is inherently narrowband with low transmission. Here, we introduce a new paradigm structure consisting of a double-grooved metallic nanostructure platform that can outperform extraordinary optical transmission structures while operating nonresonantly across broadband (Phys. Rev. Lett. 107, 163902(2011)). Our platform consists of a continuous periodic metallic nanostructure composed of an array of connected large (~100-200nm) and small (~ 15-20nm) rectangular slits. The key feature of our platform is that the optical power can be channeled through an area as small as ~ (lambda/500)2 associated with optical field enhancement and high transmission while operating across a broad wavelength band in the mid-infrared (~ 2- 20 um). We will discuss the nonresonant mechanism underlying this phenomenon based on a simple quasistatic picture that shows excellent agreement with our numerical simulations. We will also show experimental implementations of this platform and discuss pertinent results.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

8809-47, Session 12

Ultrafast slow light *(Invited Paper)*

Markus B. Raschke, Univ. of Colorado at Boulder (United States)

Surface plasmon polariton nanofocusing on scanning probe tips enables the spatiotemporal control of optical fields on nanometer length and femtosecond time scales. The resulting high field localization allows for background-free nanospectroscopy and the quantum coherent control of single emitter. One unique consequence of adiabtic plasmonic nanofocusing is the underlying divergence of the effective index of refraction over a broad bandwidth. This allows to overcome the limitations to narrow spectral ranges of the traditional methods for slow light generation. We measure the decrease in group velocity of broadband surface plasmon polariton propagation using femtosecond time-domain interferometry. We achieve a group velocity decrease to 0.2 c at the apex for a broadband 10 fs pulse. This for one provides direct experimental confirmation of the proposed mechanism of adiabatic nanofocusing. We furthermore demonstrate the potential how the precise control and engineering of the tapered plasmonic device geometry shall enable new broadband SPP-based slow light applications.

8809-48, Session 12

Laser induced electron emission from field emitter arrays with plasmonic gate electrodes

Mustonen Anna, Paul Beaud, Paul Scherrer Institut (Switzerland); Thomas Feurer, Univ. Bern (Switzerland); Soichiro Tsujino, Paul Scherrer Institut (Switzerland)

Recently laser induced electron emission from metallic nanotip arrays has been investigated for a purpose of generating high charge ultrafast electron pulses [1, 2]. In particular, short electron bunches with up to 30 million electrons were successfully generated by near-infrared laser pulses with 50 fs pulse duration, showing feasibility of high bunch charge generation by laser induced field emission for application in accelerators such as, for example, SwissFEL free electron laser facility. The experiments also showed the importance of the laser incident angle and polarization for efficient electron generation. The laser induced charge was more efficiently generated when the laser electric field was enhanced at tip apex, the effect known as formation of "hot spot" at the sharp end of a metallic wedge. Therefore, we propose to further optimize light coupling to field emitter nanotips by integrating gate electrodes that support excitation of surface plasmon polaritons at wavelengths of interest [3]. The study indicates that the submicron arrays with the plasmonic gate electrodes can increase electron yield by 30 times and simplify experimental setup by allowing efficient excitation at normal incidence. By using an advantage of SPP generated on gate surface, optical excitation of the emitter tips is also possible for double gate field emitter arrays, where the second gate is used for electron beam collimation.

References

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8809-49, Session 12

Ultrafast field-driven photoemission spectroscopy and control at metallic nanotips

Georg Herink, Lara Wimmer, Daniel R. Solli, Max Gulde, Sergey V. Yalunin, Katharina Echternkamp, Claus Ropers, Univ. Göttingen (Germany)

In this contribution, we present experimental and theoretical results on strong-field photoemission from single metallic nanotips excited by ultrashort laser pulses over a broad spectral range spanning from the visible to the far-infrared. Employing the quadratic wavelength-scaling of the ponderomotive energy, we reach deeply into the strong-field regime with electron acceleration up to several hundreds of electron volts without inducing structural damage. We find electron dynamics that emerge from the combination of optical field enhancement and nanolocalization. Specifically, for long wavelengths, an acceleration regime is identified where electrons escape the confined field within a fraction of the optical half-cycle, resulting in a field-driven acceleration and wavelength independent electron dynamics. This condition is achieved when the electron quiver amplitude exceeds the spatial decay length of the optical near-field – effectively causing a quenching of oscillatory electron motion. In this acceleration regime and for strong-fields, the photoemission yield and final kinetic energies are strongly dependent on the momentary electric field, which enables ultrafast switching of the photocurrent. In further experiments, we employ multicolor fields for efficient ultrafast photoemission gating and spectral streaking spectroscopy. Numerical simulations reveal the underlying photoemission dynamics and highlight the role of the nanostructure geometry and external parameters.

8809-50, Session 12

Carrier-envelope phase effects on strong-field emitted electrons from gold nanotips

(Invited Paper)

Christoph Lienau, Petra Gross, Bjoern Piglosiewicz, Doo-Jae Park, Slawa Schmidt, Jan Vogelsang, Carl von Ossietzky Univ. Oldenburg (Germany)

We report on the first experimental observation of pronounced carrier-envelope phase (CEP) effects on strong-field photoemission of electrons from nanometric gold tips. We believe that this is an important step towards the steering and control of the motion of electrons around metallic nanoparticles on nanometer length and attosecond time scales.

Sharp metallic nanotips irradiated with few-cycle laser pulses are sources of highly confined electron wavepackets of short temporal duration and high spatial directivity [1]. This is the case especially in the strong-field regime, where electron emission by tunneling becomes dominant over multi-photon and above-threshold ionization. For sufficiently long laser wavelengths and short pulses, electrons are accelerated to escape the near field within one half-cycle of the laser oscillation. In this case, the motion of the field-emitted electrons should be sensitive to the phase of the driving light field. We have experimentally studied the CEP effect by illuminating sharp gold tips with near-infrared light generated by a CEP-stable noncollinear optical parametric oscillator and recording the kinetic energy spectra of the emitted electrons.

[1] B. Piglosiewicz et al., Nature Photonics, under review (2013)

8809-51, Session 13

Enhanced light-matter interaction and spatial coherence in complex plasmonic systems

(Invited Paper)

Rémi Carminati, Ecole Supérieure de Physique et de Chimie Industrielles (France)

Disordered gold films exhibit original optical responses in the near infrared [1,2]. We explore the near-field plasmonic response of disordered gold films, coupling experiments [3] and theory [4]. We demonstrate the ability of these films to produce substantial changes in the spontaneous emission dynamics of nanosources of light [3]. We address basic issues, as the spatial confinement of plasmon modes close to the percolation threshold [3], the coexistence of radiative and nonradiative (dark) modes [5], and spatial coherence [6]. These films combine ease of fabrication and substantial enhancement of light-matter interaction, and are interesting platforms for fundamental and applied studies in nanophotonics.

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8809-52, Session 13

Near-field mediated plexcitonic coupling and giant rabi splitting in individual metallic dimers

Andrea E. Schlather, Nicolas Large, Alexander S. Urban, Peter Nordlander, Naomi J. Halas, Rice Univ. (United States)

In nanostructured materials, energetically-matched plasmons and excitons can undergo strong dipole-dipole interactions that greatly alter their optical properties. We report the formation of hybrid metallic dimer-J-aggregate nanostructures that exhibit coherent coupling between the localized surface plasmons (LSP) of the metallic dimer and excitons from molecular J-aggregates. By varying the diameters of the nanodisks, we can systematically tune the dimer plasmon energy across the exciton transition energy of the J-aggregate. Hyperspectral dark field spectroscopy allows us to directly measure the plexcitonic interactions in individual hybrid nanostructures. Plexcitonic coupling in these nanostructures manifests as Rabi splitting, which has been observed both experimentally and through rigorous theoretical calculations. In the strong coupling regime, the resonant scattering peak from the dipolar dimer plasmon splits into two Lorenzian peaks of different energies, which are separated by a dip at the J-aggregate exciton energy. When the plexcitonic peak energies are plotted on a dispersion curve, the Rabi splitting energy can be extracted. In this study, we show that Rabi splitting energies as high as 400 meV have been experimentally obtained for a single hybrid plexcitonic dimer. We report the highest values for plexcitonic coupling in a single nanostructure to date. In addition, the nature of the plexcitonic coupling and its dependence upon dimer geometry (i.e. disk diameter, gap distance) and field enhancement gradients inside the dimer gap have been thoroughly investigated through polarization-dependent measurements.

8809-53, Session 13

Geometric dependence of the line width of localized surface plasmon resonances

Ke Zhao, Peter Nordlander, Rice Univ. (United States)

We study the geometric dependence of damping of nanoparticles [1]. We find that for a fixed number of electrons and plasmon frequency, spherical nanoshells possesses a broader line width than ellipsoidal nanorods for excitation along the long axis. By incorporating retardation effects into a harmonic oscillator model for the plasmon resonance, we show that the geometries of nanoparticles strongly affect their plasmon linewidths through dynamic depolarization. The effect can be interpreted as a renormalization of the mass of the electrons, and subsequently, the total energy of the oscillating electron liquid. The scattering spectrum derived from our model agrees very well with the FDTD simulation, which supports our model. Since plasmon damping determines many important features and applications of LSPR, such as the Q-factor of the plasmonics devices, our study can be an important guidance for the design of nanoplasmonic systems.

References

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8809-54, Session 13

Theoretical sensitivity limit of the localized surface plasmon resonance (LSPR) to the dielectric environment

Alexei Deinega, Univ. of Toronto (Canada); Maria Bogdanova, Kintech Lab. (Russian Federation); Yurii E. Lozovik, Institute of Spectroscopy (Russian Federation); Sergiy Zalyubovskiy, Radislav A. Potyrailo, GE Global Research (United States)

We discuss maximal sensitivity limit achievable by localized surface plasmon resonance (LSPR) supported by metal nanoparticles.

We start with perturbation theory and show how derived results can be simplified under additional assumptions. These assumptions include case of negligible metal dispersion in the vicinity of resonance, case of lossless metal, and quasistatic limit. At the last case sensitivity is directly proportional to wavelength and depends on the fraction of the electromagnetic energy confined within the sensing volume (fill factor) which is less then unity. Therefore one should not expect to find optimized nanoparticle geometry with dramatic increase in sensitivity at a given wavelength. The particle shape should be chosen to have LSPR wavelength as far to the infrared, and fill factor should be optimized via the geometry of the particle.

We show that sensitivity of the LSPR is competitive with traditional surface plasmon resonance (SPR) for thin (less than 10nm) analyte layers. At the same time LSPR performs better in terms of signal to noise ratio.

All theoretical results are supported by finite-difference time-domain (FDTD) calculations for gold nanoparticles of different geometries (rings, split rings, paired rings and sandwiches). We calculate sensitivity by a shift of the peak in scattering spectra and estimate it by perturbation theory as well. We obtain good agreement between results obtained using both ways.

8809-55, Session 14

Probing plasmon resonances and local optical fields of silver nanoaggregates by electron energy-loss and one- and two-photon excited surface-enhanced Raman spectroscopy *(Invited Paper)*

Katrin Kneipp, Shima Kadkhodazadeh, Jakob B. Wagner, Harald Kneipp, Technical Univ. of Denmark (Denmark)

Enhanced local fields of plasmonic nanostructures are currently revolutionizing optical technologies. Comprehensive characterization of local fields is of key importance in further development of plasmon supported methods and devices.

Exciting capabilities for probing plasmonic structures and their local fields at high spatial resolution more than two orders of magnitude better than in diffraction limited optical experiments are opened up by using electron beams [1]. Complementary, high energy resolution in probing of local fields in hot spots can be achieved by optical methods using one and two-photon excitation along with tunable excitation lasers.

Our studies reveal the relation between local optical fields and electron energy-loss and show that in the near infrared range, which support SERS at high enhancement level, areas of highest local optical fields correlate with those of lowest electron energy-loss.

One- and two-photon excited SERS experiments at the single molecule level using tunable excitation wavelengths provide information about local fields in hot spots and their dependence on photon energy. Our studies verify experimentally the predicted increase of local optical fields in the hot spots with increasing wave lengths.

The reported experiments enable experimental validation of numerous computations of optical fields performed for plasmonic nanostructure. Also for complex nanostructures, which are not easily approachable by computation, they allow to characterize local optical fields and to identify optimum excitation wavelengths for plasmonic supported spectroscopy.

8809-56, Session 14

SERS measurement study on the interface of nanostructured plasmonic Ag gratings and thin C60 layer

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Nanostructured electrodes and interfaces can enhance light absorption in organic solar cells due to efficient light harvesting. Ultrathin films of an active layer (P3HT:PCBM) deposited on nanostructured grating electrodes show more absorption as a result of increased light trapping inside the structure. Plasmonic nanostructured electrodes with various geometries and dimensions have been fabricated on printed Polyacrylonitrile (PAN) pillars and characterized. Preliminary surface enhanced Raman scattering (SERS) measurements show significant signal enhancement (over two orders of magnitude) on nanostructured samples when compared to planar Ag substrates due to local electromagnetic field enhancement. Also conversion of PAN to graphitic carbon is evidenced in SERS spectra. The surface area was determined using underpotential deposition (UPD) of thallium and agrees with results calculated using SEM images. The FDTD simulated electric field distribution inside the samples confirms the experimental results. The magnitude of the electric field increases up to 60 times, showing SERS signal enhancement of three to four orders of magnitude depending on the dimensions of the pillars and gratings. Study of the interaction between a top organic layer (C60) and the Ag electrode will help us to understand the nanoscale charge transfer rate that is critical to optimizing organic solar cell performance.

8809-57, Session 14

Cascaded plasmon resonances multi-material nanoparticle trimers for extreme field enhancement

Seyfollah Toroghi, Chatdanai Lumdee, Pieter G. Kik, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Cascaded optical field enhancement in coupled nanostructures has attracted significant attention due to field enhancement factors that dramatically exceed those observed in isolated nanostructures. This additional field enhancement is expected to enable improved performance in plasmon related applications such as surface enhanced Raman spectroscopy, photoluminescence and nonlinear refraction and absorption. It has previously been shown that cascaded field enhancement exists in coupled nanospheres with identical composition; however this effect has not yet been studied in systems containing multiple materials. In this study, we numerically investigate the polarization-dependent optical response of multi-material trimer nanostructures composed of Au nanoparticles surrounded by two Ag nanoparticles. The silver dimer creates the strong optical near field required to drive gold nanoparticle in the cascaded field enhancement scheme. Results reveal different cascading regimes depending on particle size difference. For small size differences, clear mode splitting is observed, and relatively small field enhancement values are obtained. In the limit of large size difference between the Ag and Au nanoparticles, multiplicative cascaded field enhancement is demonstrated to occur, leading to a field enhancement factor of 20, 10 times larger than that observed in isolated Au nanoparticles. The presented structure appears compatible with chemical synthesis and assembly methods, suggesting that cascaded multi-material trimers could form the basis of biochemical sensors that require large electric field enhancement.

8809-58, Session 14

Core-satellite plasmonic nanostructures for SERS-based molecular sensing

Yuanhui Zheng, Melbourne Ctr. for Nanofabrication (Australia); Udo Bach, Monash Univ. (Australia) and Commonwealth Scientific and Industrial Research Organisation (Australia) and Melbourne Ctr. for Nanofabrication (Australia)

Research in the field of plasmonic sensing represents a hot topic nowadays due to rising demands of single molecule detection. Recently there has been a tremendous interest in surface enhanced Raman scattering (SERS) based molecular sensing using plasmonic nanostructures. An ideal SERS substrate should be extremely sensitive, highly reproducible and cheap. This requires that the plasmonic nanostructure can induce a high SERS enhancement, generate a reproducible SERS signals and can be fabricated at low cost. Many SERS-active nanostructures have been widely studied. However, these structures usually suffer from low signal enhancement, poor reproducibility or high fabrication lost. In our work, we report a low-cost, highly sensitive and reproducible near-infrared SERS sensor based on self-assembled core-satellite nanostructures. The core-satellite nanostructures were fabricated through a novel hierarchical self-assembly strategy that involves electrostatic and DNA-directed self-assembly processes. These nanostructures show strong and highly reproducible SERS activity superior to that of a commercial Klarite® SERS substrate and an ability of detecting target analytes, e.g. benzenethiol, at concentrations down to 1 nM.

8809-59, Session 14

Self-assembled fabrication of SERS-active substrates made of plasmonic nanoparticles

Nicholas Sharac, Salvatore Campione, Sarah M. Adams, Himanshu Sharma, Michelle Khine, Filippo Capolino, Regina Ragan, Univ. of California, Irvine (United States)

Coupled noble metal nanoparticles with nanometer scale inter-particle spacing induce strong local electromagnetic field enhancements at the plasmon resonance that find promising applications in bio-sensing devices, particularly surface enhanced Raman spectroscopy (SERS). Bottom-up lithographic fabrication methods have increasingly been explored for their ease of use and low costs. We have developed two unique self-assembly methods to achieve substrates with potential for SERS. We have fabricated nanocluster assemblies of 10 nm and 20 nm gold nanoparticles with spacing as close as 1 nm. Chemically modified gold nanoparticles are attached to a PS-b-PMMA thin film surface, showing preferential attachment to the modified PMMA domains. Electrophoretic deposition drives the assembly of nanoparticles, and ensures close spacing. We have also patterned periodic arrays of gold nanotriangles with initial tip-to-tip spacing below 100 nm. The triangles are made using nanosphere lithography and gold vapor deposition on a polyolefin thermoplastic. The substrate shrinks when heated, reducing inter-particle spacing down to 20 nm. Shrinking reduces tip-to-tip spacing, and has shown to tune the plasmon resonance of the arrays and should lead to higher SERS enhancements. Numerical simulations of localization of fields and plasmonic resonance locations of the two fabricated structures are performed alongside SERS measurements. For example, we have shown in the nanosphere clusters that the maximum SERS enhancement, computed as the fourth power of the local electric field enhancement between spheres, is dramatically affected by the inter-particle distance, reaching in principle values as large as 10^10 for 1 nm gaps.

8809-60, Session 14

TEM study of nanofinger structures for surface enhanced Raman scattering

Kate J. Norris, Univ. of California, Santa Cruz (United States) and NECTAR (United States); Steven J. Barcelo, Alexander M. Bratkovsky, Hewlett-Packard Labs. (United States); Junce Zhang, David M. Fryauf, Univ. of California, Santa Cruz (United States) and NECTAR (United States); Gary A. Gibson, Zhang-Lin Zhou, Shih-Yuan Wang, Zhiyong Li, Hewlett-Packard Labs. (United States); Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States) and NECTAR (United States)

Numerous applications of Surface Enhanced Raman Scattering (SERS) to chemical sensing exist, from food safety and water quality to anti-counterfeiting. It is well known that trapping a molecule in a plasmonic 'hotspot' with enhanced local field on a SERS-active substrate can very strongly enhance its Raman signal. However the structural characterization of the hotspots at nanometer scale that contributes to the significant signal enhancement is still illusive. We will discuss a Transmission Electron Microscopy (TEM) investigation of this novel high performance SERS-active substrates. These substrates consist of gold caps on deformable polymer nanopillars. The nanopillars are formed through nanoimprint lithography in large area pentamer patterns that proved to be the most efficient in our Raman studies. The gold caps are deposited on the nanopillars via e-beam evaporation. Capillary forces pull these structures together when placed in trans-1,2-bis(4-pyridyl)-ethylene (BPE) solution in ethanol, trapping the BPE molecules between the gold caps. Raman spectroscopy shows significant signal enhancement for the trapped molecules. This substrate design has yielded >1010 enhancement for the molecules trapped in the gaps. Both plan view and cross-sectional TEM were used to study the impact of the spacing between gold particles. We will discuss the results in this paper and provide the insights towards structural optimization.

8809-80, Session PWed

Using TCO nanstructures as the building blocks of nanophotonics in infrared

Shiqiang Li, Robert P. Chang, Northwestern Univ. (United States); Leonidas E Ocola, Center for Nanoscale Materials, Argonne National Laboratory (United States)

Near to mid infrared region is an important spectral region of great scientific and technological interest.. Plasmonics and nanophotonics applications to this regime is relatively recent and mainly focused on the traditional materials like silver and gold, however,there are some intrinsic limitations for them to be applied to infrared spectral region. As alternatives, degenerated semiconductors show superior performance. In this report, we demonstrate how to design and fabricate transparent conducting oxide single crystalline nanorod arrays for plasmonics and nanophotonics. By using an integrated top-down and bottom-up approach, we show that these nanorods can be grown at defined positions and with uniform height and diameter. The electric properties are superior owing to high crystallinity. It also offers unique properties such as tunability of carrier concentration and can be modeled easily by simple free carrier formulation. We pick a few examples to show that how we can design an lattice to observe various useful optical phenomena as the counterparts to those of silver and gold in the visible.

8809-81, Session PWed

Self-growing of plasmonic optofluidic waveguides

Hui Liu, Yajian Zheng, Shining Zhu, Nanjing Univ. (China)

Numerous liquid channel networks naturally occur in biological systems, such as vessel networks in animals and pipeline networks in plants. These connected channel networks exchange substances, energy, and information between tissues and organs and are important factors in sustaining life. On the other hand, optofluidic chips have attracted considerable attention in different fields. By combining liquid and light, optofluidic chips possess numerous potential applications. The substantial number of fluidic topology networks in biological systems provides a basis for the construction of a bio-inspired optofluidic topology network to realize novel, complex, and advanced applications. In this work, we report a new self-assembly method for the establishment of a plasmonic optofluidic network. Through this process, various topology structural networks that mimic biological liquid channel systems are obtained. Light propagation in the network is directly observed, and a complicated optical circuit can be realized in this network. Based on this technique, other interesting biological functions can be simulated in self-assembled optofluidic networks. Thus, these self-growing plasmonic optofluidic networks exhibit great potential for bionics and bioengineering applications.

8809-82, Session PWed

Effect of metal arrangement on localized surface plasmon polaritons in bimetallic nanoparticles

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Bimetallic plasmonic nanoparticles recently attracted attention due to promising applications in photonics, sensors, or biophysics. Among others heterogeneous arrangements the core-shell nanoparticles have been envisioned as most suitable for applications. Hence, the technique for determination of the nanoparticle structure must be precise and sensitive enough. There exist methods for composition estimation of nanoparticle colloids, but optical methods are most popular ones as fast and low-cost techniques. Various experimental methods have been suggested for fabrication of bimetallic colloid systems, such as chemical synthesis or laser ablation. In this contribution we evaluate the optical properties of Au-Ag nanoparticle colloid system prepared by laser ablation in water. Observed shift of the plasmonic wavelengths has been interpreted as presence of core-shell nanoparticle structure. The detail analysis of plasmonic properties for several metal arrangements has been done using the finite-difference time-domain (FDTD) method. The nanoparticles have been modeled as (i) core-shell nanospheres, (ii) bimetallic particles consisting of two parts (Au and Ag), or (iii) colloid consisting of pure Au and Ag nanoparticles. Results of numerical simulations show that all three investigated nanoparticle metal arrangement systems exhibit shift of the plasmonic wavelength with increase of the Ag/Au volume ratio in a similar way as recorded in the experiment. It points out that it is not possible to distinguish the metal arrangements in nanoparticles by the optical methods only and the conclusions from optical properties can be misleading. Thus optical methods can certainly prove only that bimetallic nanoparticles consist of alloy or phase separated metals.

8809-83, Session PWed

Observation of switching between SA and RSA in silver/gold-polyaniline nanocomposite films

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In the present work, attempts have been made to embed Silver (Ag) / Gold (Au) - nanoparticles into polyaniline (PANI) matrix using an easy wet chemical route. It is expected that the resulting nanocomposite will show the interesting third order nonlinear optical characteristics of Ag/Au-nanoparicles modified by the advantageous properties of the conducting polymer PANI. Structural characterisation of Ag/Au-PANI nanocomposite samples was done using X-ray diffraction and Raman studies. UV-visible absorption spectra show the presence of surface plasmon resonance (SPR) peaks centred at 410 nm and 520 nm for Ag-PANI and Au-PANI nanocomposite films respectively, which is a signature of nano dimensionality of the composite samples. Third order nonlinear behaviour of the nanocomposite films was analysed using Z Scan technique employing the second harmonic output (532 nm) of a Q-switched Nd:YAG laser (Minilite, Continuum). It is seen that Ag/Au-PANI nanocomposite film samples show simultaneous presence of saturable absorption (SA) and reversible saturable absorptions (RSA) behaviour at 50/75/100 µJ laser excitations. This switching between SA and RSA has been reported in many metal nanocomposite systems. However similar behavior in nanocomposite film samples has not been pursued much. The highlight of the present work is the observation of the switching between SA and RSA in Ag/Au polyaniline nanocomposite films. The switching behavior can be ascribed to the interplay between ground state plasmon band bleaching and excited state absorption. Two photon assisted absorption has been identified as the prime factor contributing towards the observed RSA in these nanocomposite films.

8809-85, Session PWed

Retrieval of the electrodynamic polarizability tensor for the design of magneto-electric optical nano-antennas

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Smart designs of novel magnetoelectric metamaterials can only be achieved by a thorough understanding of the response of its building blocks. The response of a single plasmonic or magnetoelectric antenna like e.g. the archetypical splitring resonator can be understood in the framework of magnetoelectric point scattering theory. Here, the characteristic quantity of the scatterer is its polarizability tensor. In this talk we present a scheme based on the surface integral equation method (SIE) (Kern & Martin J. Opt. Soc. Am. A 26, 732 (2009)), to retrieve the electrodynamic polarizability tensor of nanostructures, ranging from dielectric and magneto electric scatterers to plasmonic nanoantennas. We compare two retrieval procedures, firstly a vector spherical harmonic projection (VSH) of the scattered field, used in our recent paper “Ubiquity of Optical Activity in Planar Metamaterial Scatterers” (PRL (108), 22, 2012), and secondly a method based on the integration of the electric and magnetic effective currents obtained from SIE which allows for this retrieval to work close to interfaces and other structures. We show that the VSH is valid always while the effective current method only works for small scatterers. We demonstrate the power of this method by showing the very first ab-initio design of an optical magneto electric antenna based on a splitring antenna array that is capable of converting the emission of a single emitter in directional emission with either right or left handed elliptically polarized light. This antenna may find applicability in spin angular momentum encoding of quantum information.

8809-86, Session PWed

Plasmonic interaction in 3D multiparticle structures

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There have been growing research interest in 3D plasmonic nanostructures, which has additional degrees of freedom to tailor the optical properties. The optical spectra can be modulated by changing

the inter-particle separation and the arrangement symmetry in two independent directions/planes. Thus, multiple plasmonic coupling in the nanostructures gives rise to new hybridized plasmon mode formation. Fabrication of 3D nanostructure fabrication usually requires low-throughput and high-cost top-down processes. In this study, we propose bottom-up fabrication procedures for a 3D multiparticle plasmonic system, using an anodic aluminum oxide template. The process can provide large-area samples at an affordable cost.

The 3D plasmonic multiparticle system consists of hexagonal array of 30-nm-sized Au nanoparticles with a 60-nm-sized Au particle underneath the center of each array. The optical reflectance spectra exhibit peculiar dips in visible range, which is well reproduced by finite-difference time-domain (FDTD) simulations (Lumerical FDTD Solutions). The calculated field distribution clearly reveals the plasmonic interaction between the constituent nanoparticles and resulting hybridization of the localized modes. The simulations also suggest that the key factors to determine the unique optical features. In the experiments, the interaction between the large- and small-sized nanoparticles can be controlled by varying the template thickness. Such plasmonic coupling significantly influences the resonant mode energy and spatial distribution of the electromagnetic field.

8809-87, Session PWed

Strategies for self-organization of Au nanoparticles assisted by copolymer templates

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For the past fifteen years, the investigations of the Localized Surface Plasmon Resonance (LSPR) for plasmonic nanoparticles (NPs) has opened new perspectives for optical nanosensors. The application possibilities are all the more numerous as the fundamental studies go to the direction of single molecule sensing. What is at stake today is the development of such large scale and low cost devices.

The scientific aim is here to propose and review different strategies for organizing gold nanoparticles via the use of Polystyrene-Polymethylmethacrylate (PS-PMMA) copolymer templates. We developed both top-down and fully bottom-up processes:

1) etching of copolymer templates and use of the induced holes as nucleation sites after gold film annealing.

2) Incorporation of functionalized Au NPs in copolymer solution and organization in PS domains either by thermal annealing or Langmuir-Blodgett method

3) Incorporation of Au salts in PS-PMMA copolymer solution and in-situ synthesis and organization of Au NPs in PS domains.

These processes are original routes to organize Au NPs onto substrates. Surprisingly, the extinction optical measurements showed an expected main LSPR peak at about 550nm (for 10nm Au NPs) but also a second or even a third peak at longer wavelengths (respectively ~700nm and ~800nm). Discrete Dipole Approximation (DDA) simulations confirmed the experimental results and tend to argue that the 2nd and/or 3rd peak would come from coupling between very close Au NPs. Possible applications will be discussed.

This presentation opens new routes for large-scale fabrication and organization of Au NPs onto substrates. It could pave the way for developing new kind of sensors.

8809-88, Session PWed

Tunable sensitivity and wide dynamic range phase detection of multichannel grating-coupled SPR sensor

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We report a multichannel grating-coupled surface plamson resonance (GCSPR) sensor by utilizing a proposed phase-shift interferometer (PSI) for tuning sensitivity and wide dynamic phase detection. The grating structure of the sensor device was fabricated by nano-imprinting technique and a thin meal film was thermally evaporated onto the grating surface. In our system, a cylindrical lens with focal length of 60 mm to form a V-shaped convergent beam with incident angles ranging from 12 degree to 16 degree. Two liquid-crystal modulators (LCM) able to produce over one wavelength retardation were used to produce five-step phase shift in the PSI system. A low-cost web-camera with 130 Mega pixels was used to capture these phase shift images of the multichannel GCSPR sensor and then the five-step phase-shift reconstruction algorithm can obtain spatial phase-shift information. The phase detection sensitivity can be tuned by rotating a polarizer in front of the web-camera. Experimental result shows that detection range larger than 0.01 RIU and detection sensitivity tuning approximately from 10E-5 to 10E-7 RIU can be obtained in our system. In conclusion, this tunable sensitivity and wide range phase detection functions can provide a more flexible SPR sensor detection method. Moreover, the grating coupled and multichannel scheme can provide low-cost and high throughput detection.

8809-89, Session PWed

Surface plasmon amplification in finite-width gold stripline based on Nd:YVO4 gain crystal

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We have succeeded to amplify the surface plasmon polaritons (SPP) signal on finite-width gold stripline using Nd:YVO4 crystal (1.1% doping) as gain medium. The setup is built to allow a precise control of probing spot (λ=1064nm) on 3µm-width gold striplines using high magnification and ultra-long working distance objective (50X/0.55 NA) with CCD camera. The stripline is made by focused ion beam technique from 30nm-thick gold film which being coated on 1mm-thick Nd:YVO4 crystal using ion assisted deposition technique. The p-polarized laser at wavelength 808nm (0.2W/cm2) is employed to pump crystal gain. TM-polarized probing laser couples to SPP modes by adjusting the incident angle through prism and reflected light is directed to photodetectors.

The reflectivity versus incident angle R(θ) is measured in two cases: on planar gold film and on 3um-width gold stripline. The minimum value of R indicates the resonant angle where the incident energy is transferred to SPP (21.6 degree in film and 24.1 degree in stripline). By dividing the value of normalized reflectivity at resonant angles with and without pumping laser, the relative enhancement signal is about 55% on film and 12.5% on stripline. However the most important result is the narrowed width W of reflectivity curves with and without pumping laser obviously indicating the SPP amplification since W is linked to losses and inversely proportional to the SPP propagation length. The value of gain can be estimated by fitting Fresnel reflection equation with experimental data R(θ), this finally yields the imaginary value of gain medium ≈ -0.015, corresponding to compensation of 44% of internal SPP losses.

8809-90, Session PWed

Localized surface plasmon resonance sensor based photonic crystal fibers with nano-composite material

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Localized surface plasmon resonance-based optical chemical sensors and biosensors are the appropriate, cheap, simplified and rapid alternative to more sophisticated detection techniques. In this paper, we propose a localized surface plasmon resonance refractive index sensor based on photonic crystal fiber filled with nano-composit materials (metal-dielectric-metal) and liquid analyte. In such sensor, by introducing the model stack of inner-silver (18nm) fused silica (220nm) silver (18nm) to the air holes of the photonic crystal fiber cladding, the interactions between the liquid analyte and the nanomaterials can change the evanescent field distribution in the air holes of optical crystal fiber cladding to generate the localized surface plasmon resonance phenomenon, and measuring the change of absorption spectrum or transmission spectrum can obtain the change of refractive index of the analyte. We have got the optical field distribution of the fundamental mode, dispersion relations of plasmonic mode and core guided mode, and the relationship between wavelength and attenuation constant of the fundamental mode by by finite element method, respectively. Meanwhile, we find that more than one resonance peaks in a larger wavelength range can be achieved, which make the proposed sensor possible to precisely tune the resonance wavelength to generate multiple peak shifts. This is useful in the application of multiple wavelength sensors.

8809-91, Session PWed

Low-threshold photoinduced transformations and enhanced absorption and fluorescence of hybrid materials comprising silver nanoparticles and polymethine dyes

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Granular metal films were obtained via thermal evaporation of silver on transparent supports in a vacuum chamber at 10^{-7} mbar. Subsequent annealing for different times leads to formation of films with pronounced plasmon bands tunable over the visible. Several polymethine dyes were dissolved in alcohol and spin-coated over the supported granular silver films as well as on the bare quartz and sapphire substrates for comparison. The samples were characterized by optical spectroscopy and scanning electron microscopy.

To avoid uncontrollable damage of silver granular films in the course of the spin-coating process the samples were soaked in pure alcohol overnight. The silver granular films obtained in this way were stable enough to sustain multiple cycles of dye coating and subsequent washing in a solvent without noticeable changes of their properties checked by optical spectroscopy.

Transformations of polymethine dye molecules were studied under the action of cw and pulsed laser irradiation. The threshold of laser induced transformations of dye molecules in hybrid films was found to be much lower than that for the bear dielectric substrate. Optical density increases by 0.005 under the action of Nd:YAG laser second harmonic pulses at the fluence of 7 mJ cm^{-2}. Most interesting, in the case of a hybrid film, laser induced transformations lead to the increased absorption in the J-aggregate band while the dye layers on a bare substrate experience, albeit three times smaller, decrease of absorption. Besides photoinduced transformations, a complex interaction between plasmon and dye absorption and fluorescence bands were observed and interpreted.

8809-92, Session PWed

Angular and polarization properties of cross-holes nanostructured metallic filters

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Nanostructured metallic filters have been widely investigated since Ebbesen highlighted the role of plasmons resonances in extraordinary optical transmission for sub-wavelength structures [1]. This gave rise to a growing interest in pattern metallic layers for filtering, polarizing and display applications. Different types of structures have been studied, such as Metal-Insulator-Metal arrays, metallic patches arrays and holes arrays in a metallic layer, where the filtered wavelength is governed by the nanostructures characteristic dimensions. Regarding holes arrays, various basic shapes have been tested, especially squares, circles, triangles.

Most of the hole designs show a particular sensitivity to polarization and to azimuth angle when the incidence angle is increased. Their spectral response is thus severely dependent of impinging light properties, causing color shifts and losses of transmission. For image sensors, such errors would lead to drastic disparities in pixels sensitivity over a matrix and to distortion in color rendering.

In literature we find some examples of cross-shaped holes with low influence of polarization at normal incidence [2]. In this work we address a complete review on cross-shaped holes designs and materials composition and we identify specific ranges of cross dimensions, shape factors and period array to get conditions of spectral response stability in terms of polarization and azimuth angle, which has never been shown so far. We have determined particular structures that would allow the realization of image sensors and displays with extremely low color errors whatever the orientation and the polarization of the incident light.

8809-93, Session PWed

Modelling of ellipsoidal nanowires: control and application

Elliott Claven, Queensland Univ. of Technology (Australia)

Akimov et al explains that the distance a plasmon can travel is further if it is supported by a thicker circular nanowire, while thinner nanowires are expected to be able to increase QD coupling. Ellipsoidal nanowires may be a good compromise due to their ability to have both thin and thick dimensions. Furthermore it has been shown that the plasmon resonances along the main axis of an ellipsoidal particle is governed by the relative aspect ratio of the ellipsoid.

Using COMSOL Multiphysics we found the fundamental plasmon mode supported by an ellipsoidal nanowire and then studied this mode for various geometrical parameters, materials and illumination wavelengths. Accordingly it was found that ellipsoidal nanowires exhibit a minimum for the wavenumber and a maximum for the propagation distance at roughly the same dimensions. Highlighting that there is an aspect ratio for which there is poor coupling but low loss.

We plan to fabricate ellipsoidal nanowires using lithography. This will be done by first cleaning an ITO-glass slide and covering this slide with polymethyl methacrylate (PMMA) using a spin-coater. The next step will be to mill ellipses into the PMMA by use of a Focused Ion Beam (FIB), followed by a covering of gold/silver using a thermal evaporator and then using a lift-off process to remove the PMMA for testing of the nanowires. We hope that the results of our investigations will lead to new active and passive plasmonic devices.

8809-94, Session PWed

Resonant enhancement of Spin Hall effect mediated by scattering from plasmonic nanostructures: a polarimetric investigation

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A novel approach based on conventional polarimetry formalisms like Jones and Stokes-Mueller algebra combined with the scattering theory has been developed to analyze / interpret the spin orbit interaction (SOI) of light mediated by scattering from plasmon resonant metal nanostructures. The individual SOI effects have been analyzed / quantified via scattering Mueller matrix derived polarimetry parameters, namely, diattenuation d and retardance δ parameters. These results show that each of the SOI effects can be tuned, enhanced / optimized in plasmonic nanostructures via the diattenuation and retardance parameters achieved by choosing suitable system parameters (wavelength, size and shape of nanoparticles). We also demonstrate that the interference of two neighboring modes in plasmonic nanostructures (orthogonal electric dipolar modes in rods or electric dipolar and quadrupolar modes in spheres) can be used to effectively enhance the contributing SOI effects. The SOI is also observed to be associated with Spin Hall effect. We have also derived explicit expressions for Spin Hall Shift parameters in terms of the scattering matrix elements. The developed theory has been explored to study the role of plasmon resonances (dipolar and quadrupolar resonances in nanorods and nanospheres) in metal nanostructures and whispering gallery modes in dielectric microspheres. The results indicate that the Spin Hall Shift can also be significantly enhanced exploiting these resonance effects. The details of the theoretical formalisms for studying SOI and Spin Hall effect and the results of investigations on metal nanostructures and dielectric microspheres will be presented.

8809-95, Session PWed

Hybrid ARROW-B plasmonic waveguide coupler

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In recent years, there has been a tremendous growth on the study of surface plasmon polariton (SPP), as one of many enthralling fields of nanophotonics which probes how electromagnetic fields can be confined below subwavelength dimensions. The SPPs which propagate along metal dielectric interface can be guided through metallic nanostructure and has a vivid future for plasmonic integrated circuits (PICs). However, plasmonic nanostructures, usually suffer from metal induced attenuation which makes it impractical to send signals across entire PICs solely, through plasmonic waveguides. Therefore, integration of plasmonic waveguides with conventional low loss dielectric waveguides has become increasingly important for designing better devices.

In this paper, we have proposed a hybrid antiresonant reflecting waveguide, type B (ARROW-B) plasmonic coupler, which consists of a hybrid ARROW-B plasmonic waveguide exhibiting subwavelength confinement and a dielectric waveguide. The two dimensional modal electric field distribution and the propagation characteristics of the bound and radiation modes is evaluated and studied using finite-element-method (FEM) at =1.55 micron. The coupling characteristics for TM mode versus structure parameters and wavelength have been shown. Further, the coupling length and high extinction ratio has been calculated for the proposed structure. The directional coupler can also be used to efficiently excite the hybrid plasmonic mode with the conventional dielectric mode. This directional coupler can be potentially useful for signal routing and as a power splitter/combiner etc. between plasmonic waveguides and dielectric waveguides in future plasmonic integrated circuits.

8809-96, Session PWed

Enhancing thermal emission from patterned Pt microstructures using periodic structuring or nanoparticles

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We investigate the thermal radiation in the infrared regime of microfabricated Platinum (Pt) heaters, i.e. resistively heated wires, either with Gold (Au) nanoparticles deposited on the surface or with periodic structuring of the surface. The purpose of the work is to enhance the emissivity of the Pt heaters by modifying their surface properties. Polarization resolved thermal radiation was measured at different temperatures. Measurements show that the intensity of the thermal radiation increases by several times when nanoparticles are deposited on the microheater surface or the microheater surface is periodic structured, compared with an identical size heater but without any modifications of the surface.

8809-97, Session PWed

Simulation of arrays of metal nano-particles using a monochromatic recursive convolution finite-difference time-domain method

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The arrays of metal nano-particles can support localized surface plasmon resonance (LSPR) modes, making them suitable for coloring applications. The LSPR peaks of such arrays can be tuned by changing the structural parameters, such as, shape, size, of each particle and the interparticle distance. In this paper we study the dependence of LSPR properties of arrays on the structural parameters.

The extinction spectra of a spherical particle can be computed analytically using Mie theory. No analytical computation method is available for particle arrays. Numerical methods, e.g., discrete dipole approximation, finite-difference time-domain (FDTD) method are used [1, 2]. Here, we compute the extinction spectra of linear arrays of nano-particles using a monochromatic version of recursive convolution (RC) FDTD method [3]. We developed this method to be able to use the handbook values of permittivity of the material of the particles at each wavelength.

The simulations indicate that the position and size of the peaks of the extinction spectra are determined by the interparticle distance between any two particles and the number of particles in the array. In case of linear arrays of infinite, silver nano-cylinders, the LSPR peak can be shifted toward the longer wavelengths (red-shift) by reducing the interparticle distance. The red-shift increases as the interparticle distance becomes smaller. The peaks of extinction spectra become larger as the number of particles in the array increases.

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8809-98, Session PWed

Fourier modal method for the analysis of LSP arrays interacting with dielectric waveguides

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Based in the Localized Surface Plasmons (LSP), in recent years have been designed many nano-scale optical devices, being also developed several computational algorithms for their study and characterization.

Among these methods lies the Fourier Modal Method (FMM), also named RCWA, which is a rigorous method that solves the Maxwell equations in the frequency domain. It is based on the description in Fourier series of the structure, the permittivity and the electromagnetic field. With this formulation is possible to find the proper modes of a periodic structure and its dispersion curves as an eigenvalue problem, and also is possible to modulate the propagated light along the structure as an evolutionary state.

The FMM method allowed us to study the light interaction of a periodic array of metallic nanoparticles with a dielectric waveguide, generating near-field intensity maps of the electromagnetic field components, as well as the determination of the optical power transmitted, reflected and absorbed by the structure.

As this method allows us to characterize the LSP resonances, is possible to use it in the design of integrated plasmonic devices for sensing applications.

8809-99, Session PWed

Metallic nanostructures for controlled optical properties of surfaces

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Deterministic control of the optical properties of materials in the mid-infrared spectrum is experimentally demonstrated using periodic arrays of gold structures. By multiplexing together different sized gold squares within the unit cell of a device, we are able to demonstrate near perfect absorption of light. Using gold square sizes of 865nm and 815nm, wideband absorption, well exceeding the bandwidth that is possible when using single sized squares, is achieved. In addition, these plasmonic resonance based structures can be arranged in such a way as to generate multi-spectral band absorption, such as dual and triple spectral band absorbers. Experimental results agree very well with simulations obtained using a finite difference time domain (FDTD) technique. Electrical field profiles indicate that the primary cause of absorption is due to image induced quadrupole modes between the structured gold surface and an underlying thick gold layer.

Using a germanium substrate, we also show that structured gold surfaces can be used as thin anti-reflection coatings. Tuning of the surface reflection coefficient and phase is possible by adjusting the size of gold structures that are fabricated on a magnesium fluoride dielectric layer, allowing the total reflection to go to zero. With this tuning ability, it is no longer necessary to satisfy the condition for quarter-wavelength anti-reflection coatings. This enables metamaterial anti-reflection coatings with total thickness less than the quarter wavelength.

8809-100, Session PWed

UVA mediated synthesis of gold nanoparticles in pharmaceutical-grade heparin sodium solutions

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A photochemical-based method in which UVA light (λ=366 nm) is used for synthesizing gold nanoparticles by irradiating gold (III) chloride hydrate (HAuCl4) in the presence of pharmaceutical-grade heparin sodium (PGHEP) as a reducing and stabilizing agent in aqueous solution is presented. Different HAuCl4 to PGHEP concentration ratios were exposed to UVA for up to seven hours. The as-synthesized nanoparticles were characterized by UV-VIS and Raman spectroscopy, transmission electron microscopy (TEM), and pH measurements. The synthesized AuNPs present spherical as well as anisotropic shapes, such as oval, triangular, hexagonal sheets, rods, and some other faceted forms, with dimensions ranging from 20 nm to 300 nm. All obtained products show good temporal stability in solution. Surface plasmons differ when varying HAuCl4 to PGHEP concentration ratio. The obtained samples exhibit two absorption peaks, one in the region between 500-600 nm, and another one in the near-IR between 900-1200 nm; both peaks shift to longer wavelengths and increase their absorption intensity as the HAuCl4 to PGHEP concentration ratios increase. TEM images show the change in nanoparticles yield as well as the shape and sizes change depending on HAuCl4 to PGHEP concentration ratio variation. pH measurements suggest that acidic media promote anisotropic nanoparticle formation. Raman spectroscopy was used to find out which heparin sodium main groups attached to the nanoparticles surface, and in what amount. In summary, it is found that when modifying the reactants concentrations and keeping the UV exposition time as the only fixed parameter, different nanoparticles with distinctive characteristics can be attained.

8809-101, Session PWed

Narrow-waist metal bar infrared optical antennas

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Optical half-wave antennas comprising metal bars with a constricted waist are investigated in the mid-wave infrared regime with experiments and numerical simulations. A narrow-waist metal bar antenna is an optical antenna with a reduced width in the middle of bar compared with a rectangular bar. Narrow-waist gold metal bar optical antenna arrays with various reduced waist widths and periods are designed, fabricated, and tested. The experimental results agree well with numerical simulations. It is found that surface plasmon resonance and the resonant near fields on the resonance can be significantly enhanced by reducing the waist width of metal bar antenna. Additionally, the reduction of the waist width causes a red-shit of the surface plasmon resonance and an increased in the photon absorption cross-section in the metal bars. The findings in the work provide an additional degree of freedom for making IR optical antennas to meet various applications.

8809-102, Session PWed

Plasmonic Ag nanoparticles and nanostructures on thin substrates for enhanced energy harvesting

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Nanoparticles and nanostructures with plasmonic resonances are currently being employed to enhance the efficiency of solar cells [1]. Ag stripe arrays have been shown theoretically to enhance the short-circuit current of thin silicon layers [2]. Monolayers of Ag nanoparticles with diameter d < 300 nm have shown strong plasmonic resonances when coated in thin polymer layers with thicknesses < d [3,4]. We study experimentally the enhancement of short-circuit current and solar spectrum-averaged efficiency solar cells with thin (< 750 nm) silicon layer, when combined with a monolayer of plasmonic (Ag, Al) nanoparticles having different average inter-particle spacings. Using both simulation and optoelectronic measurements, we also research the use of Ag stripes to enhance the efficiency of thin silicon films. These Ag stripes are combined with 200 nm and 60 nm wide "teeth", which act as nanoantennas, and form vertical rectifying nanostructures on Nb/NbOx substrates. We employ spectrophotometry and high-power, focused continuous wave lasers to experimentally measure the efficiency enhancement of Ag nanoparticle- and stripe-coated thin silicon, organic photovoltaic, and Nb/NbOx films. We measure power conversion efficiency, and interpret it in terms of plasmonically-enhanced enhanced absorption, photogeneration, rectification, hot carrier effects, etc.

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8809-103, Session PWed

Rotated grating coupled surface plasmon resonance on wavelength-scaled shallow rectangular gratings

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Theoretical investigation of rotated grating coupling phenomenon was performed on a multilayer comprising 416-nm-periodic plasmon-wavelength-scaled shallow rectangular polymer grating on bimetal film made of gold and silver layers. During the multilayer illumination by 532 nm wavelength p-polarized light the polar and azimuthal angles were varied in a parametric sweep performed by COMSOL software package. In case of modulation amplitude larger than a minimal value, splitting was observed on the dual-angle dependent reflectance in two regions: i) close to 0° azimuthal angle corresponding to incidence plane parallel to the periodic pattern (P-orientation); and ii) around ~33° azimuthal angle (C-orientation), in agreement with our previous experimental studies. The near-field study revealed that in P-orientation the E-field is enhanced at the glass side with p/2 periodicity at the first minimum appearing at 49° polar angle, and comprises maxima below both the valleys and stripes; while E-field enhancement is observable both at the glass and polymer side with p-periodicity at the second minimum developing at 55° tilting, comprising maxima intermittently below the valleys or above the stripes. In C-orientation coupled plasmonic modes are observable, involving modes propagating along the valleys at the secondary maxima appearing at ~33° azimuthal and ~48° polar angles, while modes confined along the polymer stripes are observable at the primary minima, which are coupled most strongly at the ~33° azimuthal and ~56° polar angles. The secondary peak observable in C-orientation is proposed for biosensing applications, since the supported modes are confined along the valleys, where biomolecules prefer to attach.

8809-104, Session PWed

Super-weak scattering of nanopatterns in multilayer hyperbolic metamaterials

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Optical scattering is a ubiquitous phenomenon in a medium with refractive index contrast. Localized plasmonic resonances in metallic nano-particles or nano-holes leading to strong plasmonic scattering have been widely explored and utilized for sensing, detection and imaging. This general concept, however, will be overthrown in engineered metallic multilayer metamaterials. In this work, we present that engraved nanopatterns of any shapes in multilayer hyperbolic metamaterials (MHMs) become invisible in a certain band of frequencies. The invisibility is caused by so-called super-weak scattering of nanopatterns, when the permittivity of the consisting MHMs along a certain direction that interacts with the incident electrical field matches with the surrounding medium. This abnormal phenomenon is demonstrated experimentally by the optical scattering and transmission characterization of nanopatterns with various geometries in Au-Si MHMs. Such super-weak scattering is invariant to pattern size, shapes and incident wave angles, which also agrees with full-wave electromagnetic simulation results. By varying the metal filling ratio in MHMs, the working wavelength of super-weak scattering can be tuned to any colors at visible light frequencies. This kind of invisibility in MHMs may lead to potential applications in optical encryption.

8809-105, Session PWed

Fabrication of wafer scale metallic nanorings and nanotubes via argon sputter redeposition for plasmonics

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Fabrication of metallic nanostructures defined in highly ordered arrays has been achieved using lengthy electron beam lithography (EBL) steps and may be limited to metals used as well as final dimensions. We propose an alternate inexpensive and fast method void of EBL that allows for use of a number of noble and magnetic metals and tuning of metallic nanorings and nanotubes down to 50 nm. Using Argon sputter redeposition, we are able to fabricate highly tunable, wafer-scale metallic nanorings and nanotubes defined via anodic aluminum oxide (AAO) templates. The AAO templates can be grown on a variety of polished semiconducting substrates using evaporated high purity aluminum and a two step anodization process. After evaporation of a thin film of metal onto the template, inductively coupled plasma (ICP) etching using Argon is performed to physically blast the deposited metal nanoparticles within the pores of the AAO outward into ring and tube structures. The dipole surface plasmonic resonances contained within the nanotubes and nanorings are investigated with respect to structure dimensions and metal. By simply adjusting anodization, evaporation, and etching parameters we are able to highly tune the final geometry, structure, and composition of the metallic nanotubes and nanorings to diameters as low as 50 nm at the wafer scale.

8809-106, Session PWed

Quantum-plasmonic interaction: emission enhancement of Er 3+ - Tm 3+ co-doped tellurite glass via tuning nanobowtie

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Metallic nanobowtie is well known as a suitable structure for development of antennas that can be integrated on wide number of devices, especially in optical communications. Such feature is achieved due the presence of surface plasmon polariton (SPP) that provides a great charge density on nearby region from its tips. Considerable studies

have described theoretical and experimentally the influence of gap between tips on radiation emission, once this parameter may improve the local field, as such length decrease. In optical regime, the emission enhancement is due the quantum-plasmonic interaction create from tips region (localized local field) and the transitions levels (Er3+ and Tm3+ ions). However, metallic nanobowtie with absence of gap still deserve attention, because in addition to present similar properties from regular case as previously mentioned, can also interacts with different systems, like gain materials, that can be embedded thermically into the substrate. One of remarkable class of such material is rare earth ions, not only by the enhancement on measured intensity, but also its easiness to implement it on glasses, which constitute the main type of substrate adopted on plasmonic structures. In this work we performed the analysis of effects due implementation of erbium (Er3+) and thulium (Tm3+) rare earth ions into BK7 glass over a pattern of nanobowtie on absence of gap between its tips, fabricated by focused ion beam (FIB) technique from silver (Ag) and gold (Au) films. The bowties are vertically excited by an argon laser (Ar) which wavelength is 488 nm. Furthermore, computational simulations based on finite element method (FEM), were performed to verify the dependence of nanobowtie's geometry over the electric field along its symmetry axis.

8809-107, Session PWed

Plasmon enhanced single-photon detection

Gábor Szekeres, Áron Sipos, Maria Csete, Univ. of Szeged (Hungary)

Novel infrared superconducting nanowire single-photon detectors (SNSPD) were designed, which comprise a meandered pattern of niobium-nitride (NbN) stripes and different integrated plasmonic structures on silicon substrate. To enhance detection efficiency in case of 1550 nm wavelength p-polarized light illumination, integrated patterns with P-pitch (~792.5 nm) commensurate with the plasmon-wavelength at silica-gold interface were designed, while to enhance absorptance, integrated patterns with p=P/3 periodicity (~264 nm) were also investigated. In OC-SNSPDs integrated with ~quarter-photonic-wavelength nano-optical cavity closed by a gold reflector, the highest absorptance (27/63 % in P/p-pitch designs) was attained at perpendicular incidence onto NbN patterns in P-orientation, corresponding to incidence plane parallel to the stripes, due to the E-field antinode at the NbN-silica interface. In NCAI-SNSPDs, where each NbN stripe is located at the entrance of a quarter-plasmon-wavelength MIM nano-cavity, enhanced absorptance (34/85.1 % in P/p-pitch designs) is attainable at perpendicular incidence in S-orientation, when the incidence plane is perpendicular to the integrated pattern, due to collective resonances on the nano-cavity array. The longer vertical gold segments with P-pitch in NCDAI-SNSPDs, which can be embedded into the silica substrate via two-step lithography, enable to reach large absorptances at small polar angles in S-orientation, due to grating-coupling phenomenon. The highest absorptance among P-pitch designs (75 %) is attainable in NCDAI-SNSPD, and the maximal absorptance (92.7 %) in p-pitch NCDAI-SNSPD is also larger than in the counterpart NCDAI-SNSPD. P-pitch NCDAI-SNSPDs supporting coupled surface waves with potential to ensure synchronous E-field enhancement below the NbN stripes are proposed for detection efficiency maximization.

8809-108, Session PWed

Fabrication of nanoparticles for generation of force and torque at nanoscale

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Inscription of nano-grooves on thin metal films and arrays of nanoparticles is used to create patterns which scatter and absorb light with different cross sections for left and right circularly polarized light. Dielectric nanoscale hybridation of the metallic nanostructures is also realized. An optical extinction was measured from a single particle as well as from tens of nanoparticles. We use our fabrication approach introduced earlier to inscribe and center chiral groove patterns on arrays of nanoparticles without positioning errors. Numerical simulations were carried out to estimate light enhancement, force and torque generated by the nanoparticles both under plane wave and bounded light fields carrying orbital angular momentum.

Focused ion milling with sub-15 nm resolution in 50-nm-thick gold nanoparticles and film coatings can produce high fidelity patterns over write fields with cross sections up to 100 by 100 micrometers. Such high fidelity nano-writing allows to characterize optical properties of single particles as well as their ensembles. One can envisage direct write of plasmonic circuitry elements such as split ring resonators. Another promising approach to create nanoparticles which have features extending out of the film plane by tens-of-nanometers is demonstrated by combination of electron beam lithography and dry etching where sacrificial resist film is removed gradually as gold is dry-etched in the openings. After dry etching, vertical protrusions are formed near the edges of the grooves defined by electron beam lithography. Optical properties of such hybridized polymer-gold nano-wells and grooves were characterized experimentally and numerically simulated.

8809-109, Session PWed

Infrared near-perfect emitter based on complementary bowtie aperture array

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Complementary bowtie aperture (CBA) has been shown to efficiently confine and enhance the magnetic field in the optical frequency range. In this work, we demonstrate a near-perfect absorber in the infrared region based on CBA array combined with a metal ground plane. According to the Kirchhoff's law of thermal radiation, the CBA array is also a perfect emitter at the resonant wavelength, at a given temperature. Different from metamaterial-based perfect absorbers where the simultaneous electric and magnetic resonances are achieved in electric resonator and metal layer, the near perfect absorption/emission of our structure originates from the strong coupling of plasmons supported by the CBA array and the ground plane. The structure is modeled numerically and characterized experimentally by spectroscopic reflection measurement. Parametric study illustrates the flexibility of manipulating absorption and emission with our structure in the near, mid and far infrared regime.

8809-110, Session PWed

Nano plasmon array for detection of light propagation in waveguide

Seulki Kim, Chan-Min Kang, Jinsik Kim, Jungho Park, Korea Univ. (Korea, Republic of)

Surface plasmons (SP), propagating at metal/dielectric interface, have been studied in various fields such as bio and chemical sensors. Nowadays, the other applications of SP were highlighted for facilitating the all integrated optical circuit in nano space.

We introduce the design and fabrication of a periodic array of gold nanostructure for detection of light which is propagated in a SiON waveguide. The gold nanostructures are designed using COMSOL Multiphysics tools and fabricated by electron beam lithography and lift-off processes. The array is composed of 5 nano rods. The nanorod has 50 nm height, 100 nm width and 15 um length.

The enhancement of light at nano array was detected. Below the specific distance between nano array and waveguide, the nano array can detect the evanescent tail of light. The results demonstrate nanorod array can verify the fact that the incident light propagates in a waveguide or not

when optical components are densely integrated. The various geometries of nanorods array could be applied in fluorescence enhancement, high-harmonic generation and free space coupler.

8809-111, Session PWed

Optical near field imaging of localized surface plasmons modes in metallic nanostructures integrated on dielectric waveguides

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The study of surface plasmon-polaritons interactions in metallic nanostructures has been a topic of interest during last years due to their use in various areas such as the photonics, chemistry and biology. Example of use is found in biosensors for the efficient detection of biological analyte and in nanophotonic elements for on-chip photonics.

Here, we study the interactions properties of localized surface plasmons in a hybrid waveguiding structure made of bi-dimensional array of gold nanowires vertically integrated on silicon-on-insulator waveguides across the near infrared spectrum. With the use of near-field scanning optical microscopy (NSOM) in perturbation mode, we qualitatively obtained the spectral response of such hybrid structure through intensity near field maps of the light propagation. Amplitude and phase properties of the electric field are also obtained with the use of a heterodyne scattering NSOM. It is confirmed, from the NSOM images, the efficient excitation of the cut wires resonance in a guided wave configuration when the fundamental TE mode of the silicon waveguide is set as the input field. These experimental results demonstrate that metallic nanostructures integrated on silicon are suitable for the development of localized surface plasmon integrated devices.

8809-112, Session PWed

Epitaxial growth of DNA-assembled plasmonic nanoparticle superlattices

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Recently, it has been demonstrated that plasmonic nanoparticles can be assembled into a wide variety of crystalline arrays using DNA functionalization and hybridization.[1] These DNA-nanoparticle (DNA-NP) superlattices have typical grain sizes of a few hundred nanometers up to one micron, with poorly controllable edges, sizes and orientations, and this limits optoelectronic characterization and device integration. Borrowing from techniques of conventional crystal growth, we are growing DNA-NP lattices epitaxially. Using electron-beam lithography, we pattern gold on silicon in the form of the first layer of a DNA-NP crystal in any major crystal plane and with lateral dimensions over many microns. By functionalizing this substrate with DNA and treating it with complementary DNA-coated nanoparticles, we can produce a 3D structure which was seeded initially in two. By observing the layer-by-layer growth, we are able to better understand the crystallization process itself. We can also exert fine control over the size and orientation of DNA-NP assemblies, and we anticipate extending the range of particle sizes and geometries which are capable of forming crystal lattices. This will enable more sophisticated optical measurements and extend the range of properties which these materials can exhibit.

[1] Macfarlane, R.J. et al., Science 2011, 334, 204.

8809-113, Session PWed

Spectroscopic ellipsometry study of plasmon resonances of copper in uniaxial mixed oxide medium

Zahra Ghadyani, Morten Kildemo, Lars Martin S. Aas, Norwegian Univ. of Science and Technology (Norway)

We have used spectroscopic ellipsometry to study plasmon resonances of Cu nanoparticles hosted in uniaxial mixed oxide medium. The samples are prepared by low energy ion sputtering of the mixed oxide film. The plasmonic resonances observed in spectroscopic ellipsometry data confirm presence of copper nanoparticles. The ellipsometric data is fitted using a uniaxial dielectric function model containing Lorenzian oscillators to account for plasmon resonances. The spectral position of plasmon resonances are determined by adjusting the parameters of dielectric function. The size and shape of copper nanoparticles as well as properties of the surrounding medium are derived from spectral position of plasmon resonances. This study can be particularly useful in real time in situe investigation of the fabrication process.

8809-114, Session PWed

Low-loss nanophotonic waveguide simulation based on metal heterostructure surface plasmon polaritons

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In this research, the low-loss nanophotonic waveguide is simulated using 2D FDTD method. We assume that waveguide structure consists of rectangular-shaped metal heterostructure nanoparticles with dimensions of 65nm x 50nm and a surface-to-surface spacing of 50nm between adjacent particles. The nanoparticles made of Al-Ag metal heterostructue constructed with a rectangular Ag guide. The particles are surrounded by vacuum. The dielectric constant of metals is modeled using a Drude model. We use a cw source in order to excite SPPs. Time and space steps are determined based on Courant's stability condition. In our simulation, PML boundary condition is specified at four computational boundaries. Simulation results show that by converting light into the SPPs, this waveguide transfers the light energy at λ=780.2nm with propagation loss as low as 1.68dB/μm

8809-115, Session PWed

Glass-metal nanocomposite submicron structures

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Glass metal nanocomposites that is glasses embedded with metal nanoparticles (GMN) and GMN-based plasmonics and photonics

structures are studied. These materials exhibit unique optical properties governed by surface plasmon resonance (SPR) in individual metal nanoparticles resulting in local optical field enhancement, high nonlinear effects, etc. The GMN can be nanostructured with a simple and cost-effective electric field imprinting technique based on electric field assisted dissolution of nanoparticles. This means local destruction of the nanoparticles inside the glass matrix by locally applied external DC voltage. Our near field optical microscopy studies showed that GMN can be patterned with spatial resolution down to 100-150 nm. This opens a route for simple production of 2D photonics and plasmonics structures. We show that optical properties of these structures are mainly governed by the SPR. Particularly, they exhibit properties either of dielectric or metallic structures depending on the spectral range. Changing GMN parameters one can tailor characteristics of the GMN based structures that provides additional degree of freedom in their optical properties engineering. The case of 1D periodic structure and its optical response is discussed in details including the transition from amplitude to phase diffraction regime and resonant excitation of propagating modes, including recently observed in GMN surface polariton modes. The properties of GMN based optical structures make them prospective for linear and nonlinear plasmonics and photonics.

8809-61, Session 15

Silicon, plasmonics, and in between *(Keynote Presentation)*

Uriel Levy, Ilya Goykhman, Boris Desiatov, Noa Mazursky, Avner Yanai, Liron Stern, Meir Grajower, Joseph Shappir, The Hebrew Univ. of Jerusalem (Israel)

In this talk we demonstrate the role of metal optics in enhancing the performances of active silicon devices. As an example, we will show how Schotkky diode devices can be used for the detection of sub-bandgap electromagnetic radiation with improved efficiency. Both guided wave and free space configuration are demonstrated. Additional metal optics platforms for enhancing light-matter interactions will be discussed as well.

8809-62, Session 15

Engineering multimodal localized surface plasmon resonances in silicon nanowires

Li-Wei Chou, Michael A. Filler, Georgia Institute of Technology (United States)

Semiconductors, as a result of their widely tunable carrier density (10^19 - 10^21 cm-3), are emerging as promising plasmonic materials for applications in the infrared. Silicon, in particular, is inexpensive relative to the noble metals and benefits from a robust suite of processing tools due to its extensive use in the semiconductor industry. To this end, we recently reported that phosphorus-doped Si nanowires can support mid-infrared localized surface plasmon resonances (LSPRs) with quality factors comparable to those of the noble metals [1]. Herein, we demonstrate that axial control of dopant profile in individual nanowires permits complex, user-programmable, multimodal spectral responses. Highly aligned Si nanowire arrays are synthesized via the vapor-liquid-solid (VLS) technique with a combination of Si- and P-containing precursors. In-situ infrared absorption spectroscopy measurements reveal intense absorption bands (5 – 10 micrometer) with dopant concentration and shape-dependent spectral shifts consistent with longitudinal LSPRs. Discrete dipole approximation calculations confirm that the observed spectral response results from resonant absorption and free carrier concentrations on the order of 10^19 cm-3. We also observe near-field coupling between neighboring plasmonic domains, which varies as a function of intrinsic spacer length and can be described with hybridization theory. Our results highlight the utility of VLS synthesis for surface plasmon engineering in semiconductors, create new opportunities to study basic surface plasmon physics, and pave the way for applications including bond selective catalysis, ultra-sensitive molecular detection, and thermal energy harvesting.

[1] Chou, L.-W.; Shin, N.; Sivaram, S. V.; Filler, M. A. J. Am. Chem. Soc. 2012, 134, 16155.

8809-63, Session 15

Tunable and thermally stable plasmonic sensing platform: gold nanoparticles on Al2O3 coated Au films

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Substrate-based tuning of plasmon resonances on gold nanoparticles (NP) is a versatile method of achieving plasmon resonances at a desired wavelength, and offers reliable nanogap sizes and large field enhancement factors. The reproducibility and relative simplicity of these structures makes them interesting candidates for frequency-optimized sensing substrates. Prior studies showed that plasmon resonance tuning throughout the visible range and into the near-infrared is feasible. However thus far the structures have either been relatively fragile or feature relatively small tuning range. In this work, we study the optical scattering spectra of isolated 60 nm diameter gold nanoparticles on aluminum oxide (Al2O3) coated gold films with various oxide thicknesses. The structure is shown to simultaneously provide a large tuning range and high thermal stability. Dark-field scattering images of these particles reveal red ring-shaped scattering patterns. The corresponding scattering spectra show peaks at wavelengths from 690 nm to 610 nm as the Al2O3 thickness increases from 0 to 3.56 nm, as well as a weak scattering signal around 530 nm. The relative strength and polarization of these two main features is reproduced in numerical simulations, and is demonstrated to be affected by radiation from image charges in the substrate. The thermal stability of the frequency tuned substrates is investigated by high power (100 W/mm2) illumination at 633nm. While Au NP deposited directly on Au show clear spectral changes upon illumination, the addition of an Al2O3 spacer layer leads to scattering spectra that remain stable even after high power illumination.

8809-64, Session 15

Novel thin film materials for plasmonic applications

Sara Zuccon, Marco Nardello, Vanessa Polito, Alain Jody Corso, Maria-Guglielmina Pelizzo, Paola Zuppella, IFN-CNR LUXOR Lab. (Italy)

The performances of an Inverted Surface Plasmon Resonance (ISPR) biosensor based on novel materials have been studied theoretically and experimentally. The principle of ISPR is based on a maximum of reflectivity at the coupling angle instead of the common used minimum of reflectivity, this solution has not been extensively explored yet.

The sensor response has been firstly simulated by the use of a dedicated Matlab routine. Different structures involving different materials have been considered and compared, in order to find the optimized solution.

The metals have been deposited on a flat substrate made of optical glass. Different noble metals of optimized thickness have been then deposited on top of it. The substrates have been finally coupled with a prism to test the ISPR response.

The metallic layers have been deposited at our lab by Electron Beam Evaporation. The process have been optimized for each material considered.

On top of the metallic nanostructure a thin layer of Graphene (from 1 to 10 SLG) have been eventually considered both theoretically and experimentally. We tried different solutions for the deposition of this layer starting both from Graphene Oxide and Graphene (i.e. spin-coating, drop-casting, solvent-induced precipitation and the scotch-tape approach).

The metals and the graphene layers have been characterized optically at the UV-vis spectrometer and morphologically at the profilometer and AFM.

The response of the sensors has been tested at our laboratory on a dedicated optical-bench set-up based on the Kretchmann configuration with angular modulation.

The theoretical and experimental data are reported.

8809-65, Session 15

Fano resonance in silver nanoparticles in SOI structure: design of plasmonic nano switch

Venus Dillu, I. Shruti, Ravindra K. Sinha, Delhi Technological Univ. (India)

Fano resonance is a resonant scattering phenomenon resulting in asymmetric line shape. It arises when quantum interference takes place between two scattering amplitudes: one due to scattering within a continuum of states (background process) and second due to excitation of discrete state (the resonant process). Fano type resonance is observed mainly in plasmonics nanostructures, metamaterials, diffraction grating and hole/particle arrayed structures. This resonance profile has prospective applications in sensing, lasing, switching etc. In this paper we investigate potential of plasmonic nano switch as a result of Fano-resonance observed in periodically arrayed silver (Ag) nanoparticles embedded over silicon (Si) on insulator (SOI) substrate, by using 3-D finite difference time domain method. Structural parameters of the embedded silver nanoparticles were optimized giving rise to plasmon modes in the device. We find that as the device is scanned for a range of wavelength varying from visible to near infra-red, the transmission spectra exhibits Fano-line shape asymmetry for input wavelength regime near 1.3 - 1.55micron, whereas normal resonating peak is observed in the visible region. The optical properties of the switch reveal, enhancement in transmission due to strong plasmonic Fano resonance between the background and resonant processes. Sharp Fano-resonance, specific to interacting quantum systems, is exhibited by the proposed embedded hybrid design of silver nanorods into Si, which meets the condition required for high contrast switches and hence can be exploited as per anticipated results. Fano resonance in this nanorod-substrate system can also be used for designing nanoantennae, lasers, sensors, SERS etc.

8809-66, Session 15

High-nonlinearities in Si-based nanoplasmonic guides *(Invited Paper)*

Abdulhakem Y. Elezzabi, Shawn S. Sederberg, Univ. of Alberta (Canada)

In this investigation, we consider silicon-based plasmonic devices as a platform for high-non-linear field effects. 80 nm wide Silicon-based plasmonic devices are fabricated on silicon-on-insulator (SOI) substrates using processing techniques that are largely CMOS compatible, allowing them to be integrated with electronic and silicon photonic devices. Here, we will demonstrate passive 3D routing and ultrafast active switching in a silicon-based plasmonic device platform. In order to visualize the timescale of the nonlinear optical effects in the waveguides, we employ a pump-probe cross-phase modulation setup incorporating 100 fs, 1550nm laser pulses. We demonstrate high nonlinearities on these structures at pump powers of less than 1 mW and switching time scale of ~ 3ps.

8809-67, Session 16

Enhancement of nonlinear properties of metal nanostructures by passive elements *(Invited Paper)*

Martti Kauranen, Robert Czaplicki, Hannu Husu, Roope Siikanen, Jouni Mäkitalo, Tampere Univ. of Technology (Finland); Joonas Lehtolahti, Janne Laukkanen, Markku Kuittinen, Univ. of Eastern Finland (Finland)

The optical properties of metal nanoparticles depend on their plasmon resonances. The resonances give rise to strong local fields near the particles, which can enhance nonlinear interactions. However, surface defects can also support their own localized plasmonic modes and thereby lead to highly local nonlinear responses.

We have earlier shown that localized defect modes can lead to effective quadrupole effects in second-harmonic generation (SHG) from arrays of metal nanoparticles. Significant improvements in sample quality, however, have allowed the dipole limit to be reached. This opens the possibility of designing nonlinear metamaterials with truly engineered properties, which we have demonstrated by varying the detailed ordering of nanoparticles in an array.

In this paper, we present a summary of our most recent results regarding the enhancement of nonlinear properties by passive elements, which have no nonlinear response as such. More specifically, we combine noncentrosymmetric SHG-active particles with passive elements that consist of centrosymmetric nanobars. The passive elements are shown to modify the local-field distribution at the fundamental frequency, thereby enhancing SHG. The enhancement is shown to arise from lattice interactions between the two types of particles, opening new opportunities for optimizing the nonlinear properties of plasmonic nanostructures.

8809-68, Session 16

Nonlinear extreme ultraviolet light generation in plasmonic nanostructures

Murat Sivis, Claus Ropers, Univ. Göttingen (Germany)

Plasmonic nanostructures offer the possibility to control and enhance optical fields, and they play a major role for the integration of strong-field physics with nano-optics. Emerging applications involve the study of nonlinear phenomena in confined nanometric volumes, including above-threshold and strong-field photoemission, carrier-envelope-phase dependencies and electron acceleration effects in inhomogeneous light fields. Particular interest was drawn to reports of nanostructure-enhanced high harmonic generation, which may provide unique access to coherent extreme ultraviolet (EUV) radiation and attosecond pulses in compact implementations.

In this contribution, we revisit the fundamental mechanisms of the excitation and radiation processes in atomic gases interacting with optical near-fields. Specifically, we present experimental results on highly nonlinear EUV generation in plasmonic bow-tie nanoantennas and tapered hollow waveguides using ultrashort, low-energy laser pulses. We find that the detectable radiation in our experiments on bow-ties exclusively stems from incoherent fluorescence induced by multiphoton absorption and strong-field ionization. We demonstrate that the small interaction volume in nanostructures generally favors the predominance of incoherent over coherent processes, and that local intensities in the optical near-field can be gauged by a novel means that utilizes relative transition strengths. Thus, despite sufficient local intensities for ionization, no contribution from coherent high harmonic generation is observed. Furthermore, also for plasmonic waveguide structures, stable EUV emission from fluorescent transitions in various gases is presented. In addition to the aforementioned excitation mechanisms, we find strong evidence that multistep collisional processes provide an additional excitation channel.

8809-69, Session 16

Plasmoelectric potentials in metal nanostructures

Matthew T. Sheldon, Ana M. Brown, Harry A. Atwater Jr., California Institute of Technology (United States)

The resonant plasmonic properties of metallic nanostructures depend strongly on charge carrier density. While researchers have reported shifts of the resonant absorption frequency of plasmonic nanostructures due to electrostatically induced changes of charge density, the converse — the dependence of charge density and electrostatic potential on optical absorption— has been largely overlooked. Here, we report a theoretical framework and provide experimental evidence for a 'plasmoelectric effect', an optically induced electrochemical potential in plasmonic nanostructures from narrowband absorption. A simple thermodynamic model shows that, unlike the more familiar thermoelectric or photovoltaic effects, the magnitude and sign of the plasmoelectric potential depends on the frequency difference between the plasmon resonance and incident radiation.

We experimentally test our predictions by characterizing the electrical and optical response of colloids of monodisperse Au or Ag nanoparticles spin-cast on ITO films. Scanning Kelvin probe force microscopy (KPFM) determines the surface potential of device structures while varying the frequency of incident radiation near the plasmon resonance. Under 1000 mW cm-2 single-frequency illumination, we measure induced potentials of ± 15 mV from 60 nm Au particles, with a characteristic sign change for illumination blue or red of the particle absorption maximum. Additionally, power and frequency-dependent increases of optical absorption from samples under monochromatic illumination indicate shifts of the plasmon resonance when compared with the spectral response of samples under white light illumination. We observe clear evidence for the size-dependent and frequency-dependent trends consistent with our theoretical framework, providing deeper mechanistic insight and highlighting potential applications for this plasmoelectric effect.

8809-70, Session 17

Toward low-threshold stimulated emission of surface plasmon polaritons *(Invited Paper)*

John K. Kitur, Thejaswi U. Tumkur, Mikhail A. Noginov, Norfolk State Univ. (United States)

Stimulated emission of localized surface plasmons and surface plasmon polaritons (SPPs) paves a path to active plasmonics. Unfortunately, most of stimulating emission processes in plasmonic systems reported up to date have prohibitively high thresholds. At this time, we show that the stimulated emission threshold of SPPs can be reduced by an order of magnitude if the operation range is changed from visible to near-IR and multilayered metal/dielectric metamaterials with hyperbolic dispersion are used instead of simple silver substrates. The study of the relationship between the stimulated emission threshold and the density of photonic states is in progress.

8809-71, Session 17

Cross-section curvature effect in plasmonic ring lasers

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Nanolasers have shown their potential in optical communication and information storage, due to their tiny footprint, potential high modulation rate and light spot under diffraction limit. In recent years, many structures use metal as whole or part of the cavity to achieve light confinement at subwavelength scale. In this paper, we propose and compare two novel types of hybrid plasmonic lasers, both with an ultrathin insulator layer sandwiched by a ring shape semiconductor and planar silver layer. The lasers differ in their cross-section curvature on the interface of metal and insulator. Finite difference time domain (FDTD) method is used to calculate and optimize these two ring laser structures. The resonant wavelength is set around 490 nm. The ultrathin thickness of the insulator layer makes photonic modes hybridize with surface plasmon plaritons (SPPs) at Ag-insulator interface, which confines the light field strongly in the ultrathin layer. The SPPs carry high momentum and high effective refractive index to TM mode. Whispering gallery mode is achieved according to strong feedback at the ring boundary by total internal reflection. The ring lasers have relatively high Q factors, approaching 100, at 250 nm radius and mode confinement around ?2/360. The mode volume can be shrunk to 0.1(?/n)3 and 0.01(?/n)3 respectively, which leads to Purcell factors around 70 for square cross-section and 380 for circle cross-section. We discuss the curvature effects on the mode volume and on the quality factor which accounts for the high Purcell factor for the circle cross-section.

8809-72, Session 17

Controlled generation of optical vortex beams from metallic nanostructures

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Optical vortices refer to light fields with helical phase spatial distribution that leads to well-defined orbital angular momentum states characterized by a topological charge, which can formally take any integer value. Such unlimited discretization of optical information motivates the development of new designs and protocols to manage on the orbital angular momentum of light. In particular, there is a growing interest towards the elaboration of small scale toolbox to produce, detect, sort and manipulate the orbital angular momentum light. Large-scale integration potential indeed promises novel applications that are not accessible to nowadays nanophotonic technologies. Here we propose a novel universal design of material structuration that enables the generation of optical phase singularities with arbitrary topological charges. We experimentally demonstrate our proposition in the visible domain by implementing the proposed strategy to metallic nanostructures. This is done by fabricating appropriate metallic nanocircuitry and ensuing characterization of the generated optical phase singularities. The production of optical vortex beams with topological charge ranging from -6 to +6 is reported. Experimental data is compared to predicted results from our analytical modeling of the topological optical properties of the device. These findings offer a novel strategy towards singular nanophotonics.

8809-73, Session 17

Plasmonic half-waveplate based on gold nanoslit and its application to ultrasmall radial polarization converter

Miho Ishii, Kentaro Iwami, Norihiro Umeda, Tokyo Univ. of Agriculture and Technology (Japan)

? plasmonic nanoslit array as a half waveplate for visible wavelength is studied, and arranged array pattern is applied to a radial polarization converter. A gold nanoslit array which has both 180 degree phase shift and identical transmittance between TE and TM polarizations is designed and fabricated. Design parameters of the slit array are optimized by using finite-difference time-domain calculation. The optimal design parameters are determined for several wavelengths in the visible range from 440 nm to780 nm. For example, A 252-nm width 500-nm-period nanoslit array with the thickness about 350 nm can be applied to a half waveplate for 633-nm wavelength with 50% transmittance. The slit array with this design is fabricated through electron beam lithography and lift-off process, and evaluated by Senarmont method. Furthermore, four-divided slit pattern arrangement is fabricated to make an ultrasmall radial polarization converter. From the observation under polarization microscopy, characteristic transmission pattern of radial polarization is successfully observed. This technique is expected to be applied to microscale radial polarization converter array for MEMS applications.

8809-75, Session 18

Static electric field of a point charge in a two-constituent composite medium *(Invited Paper)*

David J. Bergman, Tel Aviv Univ. (Israel)

An exact calculation of the local electric potential field τ(r) is described for the case of a point electric charge where the microstructure is that of an ε1 spherical inclusion embedded in an otherwise uniform ε2 host. The calculation is based upon an expansion of ϕ(r) in the complete set of eigenstates of the static Maxwell equations for the electric potential in and around an isolated spherical inclusion [1]. In the limit where the sphere radius tends to ∞ this becomes a flat interface structure where a perfect imaging of the point charge is expected when ε1 = _ ε2 [2,3,4]. The exact calculation has some novel implications for the perfect imaging phenomenon.

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8809-76, Session 18

Plasmonic angular momentum transfer at scattering-dependent multipole modes

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Metallic nanostructures at plasmonic resonance enable enhanced transfer of optical energy, momentum, and angular momentum. For subwavelength nanoparticles, the resonance is highly dependent on the shape as well as the size of the particle. While scientists and engineers desire to control and excite different resonant modes at will, it is well known that some natural modes can never be excited by simple plane waves, while others can easily be. In this talk, a general theoretical analysis is presented to explain this selective excitation of higher-order natural modes of metallic nanopolygons. FDTD simulation results support our theory that the broken rotational symmetry of a nanopolygon enables the selective excitation of discrete higher-order natural modes, governed by a simple grating equation in the angular domain.

The nanoparticle acting as an angular grating converts one angular momentum state of light to another by enhanced transfer of angular momentum. We present the angular momentum transfer rate calculated for the dipole and quadrupole resonance of gold nanoparticles, using circularly polarized plane wave at normal incidence. The scattering-dominant dipole and quadrupole mode operate at different angular momentum modes of the nanoparticle, and also show distinct characteristics in terms of torque transfer. The spatial distribution of the electric field on the plasmonic nanoparticle as well as the intensity distribution of the scattered light field is analyzed in detail. Our analysis serves as the basis for using plasmonic nanoparticles for manipulating photon states for quantum computing, as well as for controlling mechanical torque by light.

8809-77, Session 18

Coupling between Ems waves, molecules, and a nanoparticle

Montacer Dridi, George C. Schatz, Northwestern Univ. (United States)

We report here a theoretical study of the coupling between gain media and a plasmonic nanostructure based on 3D FDTD (finite-difference time-domain) simulations. The motivation for this work is to develop a rigorous and accurate model that account for the quantum properties of the molecule (emission, state densities,..) and the EM properties of the nanoparticle.

To account for the interaction between an EM wave and a molecule, we derive the equation of polarization density P which is the expression of the action of an electric field on a given electronic transition. Maxwell equations are then modified to couple P to the EM fields. A rate equation model for a 4-level system completes this description to give the quantum temporal evolution of the state densities. The numerical scheme that we use to solve those equations is fully explicit, and is based on the standard FDTD Yee grid. Using this approach we are able to describe nonlinear gain absorption and saturation effect. We study then the optic response of a periodic array of metallic nanoparticles embedded in gain media, and we demonstrate a lasing action featuring in a stimulated emission peak in the far-field accompanied by nanoscale energy conversion in the near-field. Moreover, we investigate theoretically the effect of the enhancement of the decay rate,the so-called Purcell factor on the threshold intensity.

8809-78, Session 18

Coherent plasmonic engineering using self-assembled reduced symmetry nanostructures

Sushmita Biswas, Jinsong Duan, Krishnamurthy Mahalingam, Dhriti Nepal, Dean Brown, Lawrence F. Drummy, Ruth Pachter, Richard Vaia, Air Force Research Lab. (United States)

Plasmonic metamaterials have emerged as an area of significant interest since they enable design of tools for ultra sensitive chemical and bio-sensing, single molecule detection, nanolasing, spectroscopy, photovoltaics and photodetection. They offer a convenient platform for the study of different coherent phenomena including plasmonic electromagnetically induced transparency (EIT), Fano resonances, super-radiance and sub-radiance owing to the tunability of the interaction parameters through the geometry and design of the system. Although it is theoretically possible to observe some of these effects in simple plasmonic shapes like spheres, in practice large damping effects make them impractical to use. Symmetry breaking allows stronger coupling between the dark and bright modes in plasmonic systems manifesting these effects. We will demonstrate multiple coherent effects in self-assembled reduced symmetry gold nanorod nanosystems in particular heterodimer and Dolmen configurations enabled by the high quality and low radiative losses due to reduced surface scattering from crystalline units, of the plasmonic structures fabricated by bottom-up chemical approach. Optical characterization performed by single particle dark-field scattering microscopy correlated with scanning electron microscopy revealed multiple dark and bright plasmonic resonances in these reduced symmetry structures. Direct excitation of the resonances with electron energy loss spectroscopy further revealed the gap modes as well as the dark and bright modes in these structures. These self-assembled reduced symmetry structures demonstrate a route to improving the quality of the plasmonic structures and will be of significant interest for future design of nanophotonic devices including single photon sources, nanolasers and displays.

8809-79, Session 18

Design of a bull's eye structure based upon the far-field scattering of a subwavelength aperture

Akira Yamada, Mitsuhiro Terakawa, Keio Univ. (Japan)

The extraordinary optical transmission of light through a bull's eye structure (also referred to as a surface plasmon antenna) has been receiving much attention. A variety of recipes have been suggested for the optimization of the geometrical parameters. However, many of the previous studies show methods of optimization empirically. We present a novel concept on designing a bull's eye structure with enhanced optical transmission of a single-wavelength optical source. By using finite-difference time-domain method, we calculated the electric field intensity of the far-field scattering of a subwavelength aperture on a thin gold film. Based on the peak positions of the concentric electric field intensity on the film surface, we determined the optimal positioning between the central aperture and its nearest groove. A fairly optimal periodicity of the groove structure can be determined from the same concentric electric field intensity distribution. By improving other structural parameters on the basis of the parameters determined above, we have succeeded in designing a bull's eye structure with a transmission factor of 60.9. Transmission of light was normalized to the hole area for calculations. Our method of designing a bull's eye structure for enhanced transmission of a single-wavelength optical source is performed under a novel idea, contributing to applications such as enhancing sensitivity of silicon infrared sensors.

8810-1, Session 1

Measurement of the range and transport properties of optical tractor beams

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An optical tractor beam is a travelling beam of light that transports material back to its source. Several schemes to create such a beam have been proposed and a few have been successfully demonstrated experimentally, among these optical conveyors that deterministically transport micrometer-scale objects. In addition to their useful and interesting transport properties, optical conveyors have been predicted to act as optical traps with exceptionally large axial trapping stiffness.

Here, we describe recent measurements of the transport properties and trapping characteristics of optical conveyors projected with the holographic optical trapping technique.

These measurements reveal how these practical tractor beams' capabilities will differ from predictions of idealized models as their range is extended from micrometers to millimeters and beyond.

8810-2, Session 1

Experimental demonstration of optical transport, sorting and self-arrangement using a 'tractor beam'

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We experimentally and theoretically demonstrate particles delivery sorting in the geometry of "tractor" beam. Particles direction is controlled by polarization of incident beams. Since the particles motion depends on their size, we also demonstrate optical sorting of colloidal particle suspension (i.e. mixture of micrometer-sized particles of various diameters or compositions) by Gaussian beam of diameter 60-100 micrometers. We observed self-arrangement of microparticles into optically bound structures that significantly changed their behaviour in "tractor"beam.

8810-3, Session 1

(Not) just torquing around

Gabriel C. Spalding, Illinois Wesleyan Univ. (United States); Christine E. M. Demore, Zhengyi Yang, Institute for Medical Science & Technology (United Kingdom); Patrick M. Dahl, Illinois Wesleyan Univ. (United States) and Institute for Medical Science & Technology (United Kingdom); Peter Glynne-Jones, Univ. of Southampton (United Kingdom); Andreas Melzer, Michael P. MacDonald, Sandy Cochran, Institute for Medical Science & Technology (United Kingdom)

Modern studies have reshaped our thinking about the linear and angular momentum carried by light (and other wave/particle bombardments), and about both the mathematical bases and language used for thinking about transfer of momentum by propagating beams. Acoustic analogies can play (and have played) a useful role in clarifying the meaning of some recent predictions, and in raising issues regarding the language in common usage for describing transfer of beam momentum. For a wide range of topological charges, we have simultaneously measured the transfer of (so-called "orbital") angular momentum and the axial "radiation pressure" acting upon an acoustically levitated absorber, resulting in a simple, direct demonstration of theoretical predictions for the ratio of these two effects. We have also examined the influence of locally off-axis "skew" momentum in contexts receiving significant recent attention.

8810-4, Session 1

Negative optical forces at dielectric interfaces for long range particle manipulation

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Optical "tractor beams" have attracted much interest recently because of their intriguing capabilities for micromanipulation. A tractor beam can exert a "negative" force (NF) that pulls the scatterer in a direction opposite to the propagation of light, in contrast to the usually "positive" push exerted by radiation pressure. The fundamental requirement for NF to occur is the increase of the momentum of light during the process of light scattering. Approaches known so far require non-paraxial incident beams or some exotic media such as gain media for NF to appear. We demonstrate that stable NFs are possible even when using unstructured paraxial beams without presence of any gain or left-handed media. Our approach is based on universal characteristics of optical forces acting on objects at the interface between different dielectric media. Namely, according to Minkowski's momentum transformation theory, when going from medium with lower to higher refractive index, the momentum of light should increase. To verify the concept of the surface assisted NF, we performed a systematic experiment with surface bound dielectric microscopic objects. We demonstrate distinct directional motion against the beam propagation over distances of approximately 200um. The experiment provides new insights for understanding surface effects in momentum exchange and can also assist in developing and evaluating microscopic theories of optical forces at interfaces. The simple scheme and the robust experimental implementation may find a plethora of applications in developing novel micromanipulation approaches and for studying interfacial phenomena.

8810-5, Session 1

Properties of oscillating refractive optical wings with one reflective surface

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In the last few decades, progress in the development of optical micromanipulation technologies has been extensive with the integration of phase modulation elements and other beam shaping devices, yet there is still room to grow in the realm of object shaping. Object shaping is the use of microscopic optical elements with specified geometric designs that allow forces from radiation pressure to be predefined without the need for specialized light sources. Optical wings are refractive cambered rods that experience a transverse lifting force under uniform illumination. When rotated away from normal incidence, a specialized optical wing has an intrinsic restoring torque that returns the wing to a sun-facing (or source-facing) orientation. This discussion will address how such

wings may be designed to sustain efficient thrust while also providing significant restoring torque to the wing. This is accomplished by the inclusion of a reflective surface on the refractive wing. Torsional stiffness and orbital periods will be presented for a set of optical wings. Effects of broadband illumination, drag, and gravity will be considered using numerical results from ray-tracing analyses. These results demonstrate the potential for development of passive sun-tracking devices for applications in microbiology and space flight systems. Object shaping presents a second modality for control in optical micromanipulation, and with further development of optical wings new applications may be afforded that today are not possible. Our goal is to inspire researchers to look to optical wing technology as a potential solution to the specialized problems in their own research.

8810-6, Session 1

Non-conservative scattering forces on small particles

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Light forces on small particles may be described as the sum of the dipole or gradient force and the radiation pressure or scattering force [1,2]. Radiation pressure is traditionally considered proportional to the Poynting vector. However, for inhomogeneous waves, there is an additional contribution to the scattering force that can play an important role in determining the actual forces on nanometer sized particles [3]. This additional contribution has been shown to be proportional to the curl of the spin angular momentum of the light field [4], affecting to dielectric and magneto dielectric particles [5-7].

In some specific cases like, for example, crossed circularly polarized standing waves, the field distribution shows regions in which the electric and magnetic fields are parallel corresponding to a null Poynting vector [8]. Although the average value of the momentum density, proportional to the Poynting vector, is zero in these regions, there are scattering forces acting on small dielectric particles due to light's spin force. We will discuss the differences between crossed linear [9-11] and circularly polarized waves and the intriguing interplay between the momentum and spin densities and the force on magneto-dielectric particles.

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8810-7, Session 1

Optical forces controlled by the photons spin

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Optical radiation forces are the mechanical manifestation of the transfer of the linear momentum of light to matter, which basically occurs when light is reflected, refracted, scattered or absorbed in the course of its propagation. Here we report on the full control of the optical radiation pressure at fixed photon flux and incident angle by controlling the photon spin. The experimental demonstration is achieved by using transparent microspheres with typical size of 10 micrometers that enable a strong coupling between linear and angular degrees of freedom of a light field. As result the spin of photons can be used to fully control optomechanical effects driven by the radiation pressure of light. A careful analysis of the possible contribution of the usual optical scattering force is considered and an experimental arrangement is proposed to cancel its contribution in our experiments. This allows us to present an unambiguous demonstration that is quantitatively validated analytically with a good agreement. Moreover, envisioned applications are discussed and experimental proofs-of-principle are presented. These results should contribute to the development of optofluidics and application potential is expected, for instance for the pharmaceutical industry, angular momentum driven nanoactuation or optical sailing.

8810-8, Session 2

Tweezing at extremes *(Invited Paper)*

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Diamond anvil cells allow the behavior of materials to be studied at pressures up to hundreds of gigapascals in a small and convenient instrument. However, physical access to the sample is impossible once it is pressurized. We show that optical tweezers can be used to hold and manipulate particles in such a cell, confining micron-sized transparent beads in the focus of a laser beam. Here, we use a modified optical tweezers geometry, allowing us to trap through an objective lens with a higher working distance, overcoming the constraints imposed by the limited angular acceptance of the anvil cell. We demonstrate the effectiveness of the technique by measuring water's viscosity at pressures of up to 1.3 GPa. In contrast to previous viscosity measurements in anvil cells, our technique measures absolute viscosity and does not require scaling to the accepted value at atmospheric pressure. This method could also measure the frequency dependence of viscosity as well as being sensitive to anisotropy in the medium's viscosity.

8810-9, Session 2

Optical fabrication and manipulation of semiconductor nanoparticles in superfluid helium

Yosuke Minowa, Yohei Nawaki, Shinya Okamoto, Masaaki Ashida, Osaka Univ. (Japan)

Non-contact manipulation technique of semiconductor nanoparticles or quantum dots is demanding and challenging, which will expand the possibilities to construct quantum-dot-based devices through bottom-up approach. In particular, the technique available under low temperature condition is crucial, because their quantum nature will disappear as the temperature increases. Optical manipulation is one of the widely accepted techniques to control the motion of microparticles and atoms, which utilizes light pressure or light momentum transfer to change the material's momentum. However, researches on optical manipulation of semiconductor nanoparticles are scarce. The difficulties arise from the relatively small polarizability, which normally tends to decrease with decreasing the particle's size in nanometer regime. Here we report on the transportation of ZnO nanoparticles in superfluid helium with the aid of the light pressure. The nanoparticles were fabricated via laser ablation of ZnO sintered tablets in superfluid helium. Many micro/nanoparticles were dispersed after the ablation. Only the nanoparticles were transported

in-situ with the irradiation of the exciton-resonant light. The excitonic resonance is expected to enhance the light matter interaction at low temperature. The transported nanoparticles showed strong ultraviolet and weak visible luminescence at room temperature. This indicates that the nanoparticles contain fewer defects than the original target tablet. Our successful implementation of the optical manipulation under low temperature condition would open up a new route for precision control of the nanoparticle motion.

8810-10, Session 3

Testing quantum physics in space using optically trapped nanospheres *(Invited Paper)*

Rainer Kaltenbaek, Univ. Wien (Austria)

What is the reason for the striking difference between the microscopic quantum world and the macroscopic classical world? Is it only quantum decoherence or is there an unknown mechanism leading to the decoherence of increasingly massive objects? This question has been investigated in matter-wave experiments with ever larger objects, but these experiments quickly approach the limits of what is still possible on Earth (time of flight, low-vibration environment). At the same time, there has been impressive progress in space technology, and space is becoming a promising alternative for tests of quantum physics with massive objects. For example, high-precision accelerometers and micro-propulsion can provide a micro-gravity environment far better than what is achievable on Earth, and optical technology, like that developed for LISA Pathfinder, paved the way for quantum optomechanical experiments in space. Here, we will present results of recent studies aiming at the realization of a space mission testing the foundations of quantum physics in a parameter regime far beyond that of existing experiments. In particular, we will discuss DECIDE, where a dielectric nanosphere is prepared in a Schrödinger-cat-like state of being in two clearly distinct positions at the same time. This leads to double-slit-type interference with a visibility we can then compare to the predictions of quantum theory. With DECIDE, it will be possible to distinctly test several prominent theoretical models that predict deviations from quantum theory - for example: the Diósi-Pensrose model, the continuous-spontaneous-localization model of Ghirardi, Rimini, Weber and Pearle, and the model of Károlyházy.

8810-11, Session 3

Realisation of a microscopic gyroscope by an optically trapped rotating microparticle in vacuum

Yoshihiko Arita, Michael Mazilu, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

The interaction between light and matter on very small energy scales has emerged as a powerful playground for the elucidation of many physical principles. In this arena, cavity optomechanics has promised new insights into the interplay between optics and quantum physics for macroscopic objects [e.g. Chang et al, PNAS 107, 1005, 2010]. As such there has been a drive for quantum state preparation using macroscopic objects [e.g. Li et al, Nat. Phys. 7, 527, 2011]. Remarkably, rotating objects at absolute zero temperature can spontaneously emit energy, and thus exerts pressure on a nearby object (dynamic Casimir effect) due to quantum fluctuations [e.g. Manjavacas et al, PRA 82, 063827, 2010]. However, to date, there is a notable absence of appropriate experimental systems to explore such regimes. To address this challenge we demonstrate the simultaneous optical trapping and rotation of a microparticle in vacuum. A birefringent microparticle is rotated by a circularly polarized trapping laser beam at rates exceeding 5MHz. Parametric coupling between the rotational and translational degrees of freedom of the trapped object, offers original perspectives on particle dynamics. We show a direct observation of spin stabilization of the trapped particle along the rotational axis in the absence of any "active" feedback method both in experimental and theoretical studies. We attribute this self-stabilization of the rotating particle akin to a microscopic gyroscope effect. This system presents a powerful route to explore new directions in cavity optomechanics and a step towards measuring rotational frictional forces both adjacent to surfaces and in vacuum.

8810-12, Session 3

Micromanipulation of multiple trapped, rotating particles in vacuum

Sayantan Ghosh, Yoshihiko Arita, Tom Vettenburg, Michael Mazilu, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Investigation of challenging fundamental phenomena such as mesoscopic quantum entanglement requires cooling of the mechanical modes of oscillators to their quantum ground motional states. To reach this regime, the coupling between objects and their thermal environments must be minimized which in turn limits decoherence in the system. In this context, optical trapping of microparticles in vacuum is an ideal system for investigating the quantum-classical interface, due to its near-perfect isolation from the thermal environment. Recent advances have made cooling of an optically trapped single microparticle with counter propagating dual beams to millikelvin temperatures using active feedback cooling methods. Herein, we demonstrate a compact holographic optical tweezers system to simultaneously trap and rotate multiple microparticles in vacuum. The unixial crystals of vaterite mircoparticles of 4.4mum in diameter are trapped in vacuum with circularly polarized light at aberration corrected multiple foci, which are generated by a spatial light modulator (SLM). The positions of the individual trapped particles are controlled by dynamic reconfiguration of the SLM masks, which allows a minimum particle seperation of $1mu$m. We can simultaneously record the translational and rotational motion for all trapped objects using a single photo-detector. Rotation rates of up to $lesssim1$MHz (with higher harmonics) accompanied by sidebands are observed in a series of power spectra in a wide range of vacuum pressures. The ability to "trap and track" multiple particles in vacuum could possibly lead to the development of powerful optical methods to explore the quantum-classical interface while also paving the way to study fundamental processes such as rotational vacuum friction.

8810-13, Session 3

Quantitatively measuring the orbital angular momentum density of light

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Although many techniques are efficient at measuring optical orbital angular momentum (OAM), they do not allow one to obtain a quantitative measurement for the OAM density across an optical field and instead only measure its global OAM. Numerous publications have demonstrated the transfer of local OAM to trapped particles by illustrating that particles trapped at different radial positions in an optical field rotate at different rotation rates. Measuring these rotation rates to quantitatively extract the OAM density is not only an indirect measurement but also a complicated experiment to execute. In this work we theoretically calculate and experimentally measure the OAM density of light, for both symmetric and non-symmetric optical fields. We outline a simple approach using only a spatial light modulator and a Fourier transforming lens to measure the OAM spectrum of an optical field and we test the approach on superimposed non-diffracting higher-order Bessel beams. We obtain quantitative measurements for the OAM density as a function of the radial position in the optical field for both symmetric and non-symmetric superpositions, illustrating good agreement with the theoretical prediction. The ability to measure the OAM distribution of optical fields has relevance in optical tweezing, and quantum information and processing.

8810-14, Session 3

Feedback enhanced precision in optomechanical sensors

Warwick Bowen, Glen I. Harris, David L. McAuslan, Joachim Knittel, The Univ. of Queensland (Australia); Ulrik L. Andersen, Technical Univ. of Denmark (Denmark)

The problem of estimating an unknown force driving a linear oscillator is revisited. When using linear measurement, feedback is often cited as a mechanism to enhance bandwidth or sensitivity. We show that as long as the oscillator dynamics are known, there exists a real-time estimation strategy that reproduces the same measurement record as any arbitrary feedback protocol[1]. Consequently some form of nonlinearity is required to gain any advantage beyond estimation alone. This result holds true in both quantum and classical systems, and in the general case of non-Gaussian noise. Recently, feedback enhanced incoherent force sensing has been demonstrated [Nat. Nano. 7, 509 (2012)], with the enhancement attributed to a feedback induced modification of the mechanical susceptibility. As a proof-of-principle we experimentally reproduce this result through straightforward filtering[1]. To prove the benefit of feedback when nonlinearities are present we apply feedback induced damping to suppress the mechanical parametric instability of a microtoroid cavity optomechanical system. This enables a 5.4 fold sensitivity improvement, with a final displacement sensitivity of 1.8 attometers-per-root-Hz[2]. This is the first time feedback has been used to enhance sensitivity in cavity optomechanics. By clearly demarcating where feedback offers an advantage, our results both clarify a significant ambiguity in the optomechanics and force sensing communities, and contribute towards ultraprecise force sensing with linear oscillators.

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8810-15, Session 3

Enhancing micromechanical measurement with squeezed light

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The quantum nature of light places a fundamental limit on the sensitivity of optical measurements. In circumstances with constrained optical power, this limit may only be surpassed using non-classical resources. Despite the promise of non-classical resources, to date the sole example of a real application is in interferometric gravity wave detection where the optical power is constrained due to absorptive heating. Much broader and widely discussed applications are possible in the areas of quantum optomechanics, where ultimately a non-classical light field interacts with a non-classical mechanical oscillator, and biological sensing, where low light levels are often required to avoid damaging the specimen. Here we report two distinct experiments which use squeezed light to, for the first time, achieve quantum enhanced sensitivity in biological[1] and cavity optomechanical contexts[2], with 2.7 and 0.7 dB of enhancement achieved, respectively. The biological experiments, particularly, allow quantum enhanced microrheology to be performed on the cytoplasm of a Saccharomyces cerevisiae yeast cell, revealing subdiffusive motion with 64% improved bandwidth over the equivalent classical measurement. This provides a pathway towards microrheology of cell mechanics and the cytoskeleton at high frequencies, where motion amplitudes are beneath the sensitivity of current technology. These results present an important first step towards both surpassing the standard quantum limit of measurements using non-classical light, and applications of quantum light in biology.

8810-16, Session 3

Optomechanics at microwave frequencies: mechanical resonators coupled to microwave cavities and superconducting qubits

Mika A. Sillanpää, Aalto Univ. (Finland)

Micromechanical resonators affected by radiation pressure forces allow to address fundamental questions on quantum properties of mechanical objects, or, to explore quantum limits in measurement and amplification. A new setup for the purpose is an on-chip microwave cavity coupled to a mechanical resonator. We run various experiments in the setup. Under blue sideband irradiation, we demonstrate the possibility of building a mechanical microwave amplifier, with noise properties approaching the quantum regime. On the red sideband side, we show how one can couple mechanical resonators via the cavity bus, while simultaneously cooling the mechanical modes very close to the ground state of motion.

One can add intriguing features to the setup by including a superconducting qubit, a quantum two-level system. Such a hybrid approach will allow for combining the benefits of each subsystem, such as the long lifetime of phonons, together with the machinery learned with superconducting qubits. Our superconducting transmon qubit interacts with a 70 MHz phonon mode in a micromechanical resonator. We operate the qubit in the circuit cavity quantum electrodynamics (circuit QED) architecture, where the qubit is coupled also to a microwave cavity. Hence, the combined setup represents an artificial atom coupled to two different cavities. We measure the phonon Stark shift, as well as the splitting of the qubit spectral line into motional sidebands, which feature transitions between the dressed electromechanical states. In the time domain, we observe coherent conversion of qubit excitation to phonons as sideband Rabi oscillations.

8810-17, Session 3

Title to be announced *(Invited Paper)*

Tobias J. Kippenberg, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No Abstract Available

8810-18, Session 4

Effective medium approach to compute optical stress

Jack Ng, Hong Kong Baptist Univ. (Hong Kong, China); Che TIng Chan, Hong Kong Univ. of Science and Technology (Hong Kong, China); Wujiong Sun, Fudan Univ. (China)

Light can exert a force on material objects, which may be computed by a surface integral of the Maxwell stress tensor over a surface that encloses the entire object. However, it is also highly desirable to know the optical stress (e.g. to deform a cell). In principles, the stress can be given by the divergence of the stress tensor. Unfortunately, there are still controversies in what is the appropriate stress tensor inside a medium.

Consider an artificial effective medium, for example, consisting of a periodic or random array of dielectric cylinders with sub-wavelength cylinder size and lattice constant. The stress will be calculated by two

methods. The first method is a rigorous but slow microscopic approach where the stress is defined as the force per unit area, and the force can be computed by Maxwell stress tensor. The second method is a very efficient effective medium approach where the cylinder array is treated as an effectively homogeneous medium and the stress for that effectively homogeneous medium is calculated directly using the divergence of three commonly employed stress tensors. It turns out that only the stress tensor derived from free energy, which takes into account the electrostriction, gives consistently correct results. In other words, MST and its "macroscopic generalization" have failed.

Situations other than dielectric cylinders will also be discussed. More examples with different composition and lattice structures will be considered.

8810-19, Session 4

The kinetic subsystem of light and its role in optical manipulation

Brandon A. Kemp, Arkansas State Univ. (United States)

Optical manipulation has allowed for an increase in understanding across scientific fields including biology, chemistry, and atomic physics. Unfortunately, there is still significant debate as to how the dynamics of optical-matter systems should be modeled. The reason for this is the myriad of formulations for the electromagnetic momentum and force density. While significant advances have been made in recent years to interpret the different formulations of electrodynamics, there remains some confusion. Most formulations include contributions from both matter and field. They may be interpreted as providing the canonical, total, or wave momentum, stress, and force. Examples include the well-known Gordon and Minkowski momenta. Conversely, it is widely accepted that the Abraham momentum of light corresponds to the kinetic subsystem. Changes in the kinetic momentum thus should provide center of mass-energy translations of matter providing a route to deriving equations of motion in optical manipulation experiments. In this paper, the idea of a kinetic formulation of electrodynamics is discussed. Consideration will be given to the three viewpoints which are most commonly argued. First, the kinetic subsystem should be postulated as a fundamental tenant of electrodynamics. Second, the kinetic subsystem of electrodynamics should not be postulated, but rather deduced by experimental and theoretical considerations. Third, a kinetic subsystem of electrodynamics cannot be uniquely defined in matter because the fields inside matter cannot be uniquely measured. Finally, it will be argued that identification of the kinetic subsystem of a particular optical manipulation experiment is not necessary nor preferred in most cases.

8810-20, Session 4

Electromagnetic field and force distribution inside matter

Masud Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States); Armis R. Zakharian, Corning Incorporated (United States)

Using the Finite Difference Time Domain (FDTD) technique, we use numerical solutions of Maxwell's equations to compute the distribution of electromagnetic fields and forces inside material media. The media are generally specified by their dielectric permittivity epsilon(w) and magnetic permeability mu(w), representing small, transparent dielectric/magnetic objects such as micro-beads. Using two formulations of the electromagnetic force density, one due to H.A. Lorentz (1892), the other due to Einstein and Laub (1908), we show that the distribution of force inside a given object can differ substantially between the two formulations. This is remarkable, considering that the total force experienced by the object is always the same, irrespective of whether the Lorentz or the Einstein-Laub formula has been employed, The differences between the two formulations should be accessible to measurement in deformable objects.

8810-21, Session 4

Optical forces on particles embedded in a dispersive medium *(Invited Paper)*

Israel De Leon, Sangeeta Murugkar, Zahirul Alam, Eliot Bolduc, Univ. of Ottawa (Canada); Robert W. Boyd, Univ. of Ottawa (Canada) and Univ. of Rochester (United States); Mohammad Mirhosesini, Mahmudur Siddigui, Omar Magaña-Loaiza, Univ. of Rochester (United States); Jerry W. Kuper, TOPTICA Photonics, Inc. (United States); Peter W. Milonni, Univ. of Rochester (United States); Zhimin Shi, Univ. of South Florida (United States)

Theoretical arguments suggest that the magnitude of the force exerted by a light beam on a dielectric particle may depend on the group index of the particle and on the group index of the medium that surrounds it. Since group indices can vary over a significant range, this observation suggests that significant control of optical forces may be achievable.

In this work we describe the status of our experimental effort aimed at determining the dependence of optical forces on group and refractive indices. We also discuss how laboratory results of this sort can help distinguish between the Abraham and Minkowski models for the momentum of a photon in a material medium.

8810-22, Session 4

Holographic reconstruction of optical forces *(Invited Paper)*

Gregor Thalhammer, Andreas Niederstätter, Stefan Bernet, Monika Ritsch-Marte, Innsbruck Medical Univ. (Austria)

According to Newton's law, collecting the light deflected from a trapped particle with a high-NA condenser lens and imaging the intensity distribution at the back-focal-plane provides direct information on the trapping force. This approach has been used to monitor the (radial and axial) optical force acting on a single trapped particle of arbitrary shape. We show that this approach can become even more powerful when combined with holographic reconstruction of the scattered light field. With phase and intensity information at hand, it is possible to simultaneously measure the force on several particles, and to assign each particle its own local force profile.

8810-23, Session 5

Quasi-Bessel hollow beam as optical guide for micro-particles

Andrei V. Rode, The Australian National Univ. (Australia); Li Li, The Australian National Univ. (Australia) and Sun Yat-Sen Univ. (China); Niko Eckerskorn, The Australian National Univ. (Australia); Richard A. Kirian, Deutsches Elektronen-Synchrotron (Germany); Jochen Kuper, Deutsches Elektronen-Synchrotron (Germany) and Univ. Hamburg (Germany); Daniel P. De Ponte, Deutsches Elektronen-Synchrotron (Germany); Wieslaw Z. Krolikowski, The Australian National Univ. (Australia); Henry N. Chapman, Deutsches Elektronen-Synchrotron (Germany) and Univ. Hamburg (Germany)

Coherent diffractive x-ray imaging of individual biological macromolecules with Free Electron Lasers (FEL) requires a "touch-free" high-precision particle injection method to deliver individual biological molecules or nanoparticles into the micron-sized focus of an x-ray beam, both in vacuum or in a gas environment, and operating collinear with a particle laden gas stream produced by an aerodynamic lens. To address this challenge we developed an optical quasi-Bessel pipeline with a hollow core for guiding particles to a focal spot of FEL of ~3 μm

in diameter. We generated the superposition of the quadratic phase of a lens and an axicon with a 0.5° base angle using a phase-only spatial light modulator (SLM) to form a low-diverging first order Bessel beam. The beam was further re-imaged to form a centimetre-long 'syringe' beam with ~7μm diameter and approximately 2000 length-to-diameter aspect ratio. The divergence of the beam was controlled by changing the effective focal lens in the hologram. The SLM-based optical beam was compared with a similar beam composed using physical optical elements. When used in conjunction with an aerodynamic lens the optical forces assist the migration of particles to the centre of the gas flow. The experimental tests were conducted with 5-μm size graphite spherical particles to evaluate the optical force and to estimate the scaling to sub-micron particle size. We present estimated optical forces exerted on the particles and the stiffness of trapping in the transverse plane, both depending on the particle size, optical reflectance, laser power, and background-gas pressure.

8810-24, Session 5

Manipulation of optically levitated particles

Oscar K. Isaksson, Magnus Karlsteen, Chalmers Univ. of Technology (Sweden); Dag Hanstorp, Göteborgs Univ. (Sweden)

We are able to levitate a single oil drop for up to six hours, inside a glass cell, using a vertically aligned laser beam. The drop is trapped just above the focus formed by a 30mm lens. The drop is then made to oscillate in an AC-field applied over the cell. The amplitude of the movement is large enough to be observed by the bare eye.

Scattered light from the laser beam is imaged on a position sensitive detector. The amplitude of the oscillations depends on the amplitude of the electric field and the q/m ratio of the oil drop. The charge is reduced by exposing the drop to alpha particles. The absorption of an alpha particle causes electrons to be detached from the drop. During exposure we observe distinct reductions in the amplitude of the oscillations, and after some time the oscillations starts to increase in amplitude again. The phase of the oscillations with respect to the driving AC electric field then reverses. This means that all excess electrons have been removed, and the drop is now positively charged.

As the next step, we will investigate the size of the reduction in the steps, with the aim to determine how many electrons that are removed by each alpha particle. The ultimate goal is to observe the sequential removal of single electrons from the drop.

8810-25, Session 5

Optically trapped aerosol dye laser

Alper Kiraz, Alexandr Jonas, Yasin Karadag, Mehdi Aas, Koç Univ. (Turkey); Suman Anand, David McGloin, Univ. of Dundee (United Kingdom)

Airborne particles such as aerosols can be readily localized and studied over long periods of time using optical tweezers. Aerosols can also be used as a microcavity to create lasers if the aerosol contains a gain material. The ability to hold such small lasers opens up new possibilities in sensing and may offer new ways to probe airborne particles, while the control over droplet dynamics that can be achieved suggests that tunable laser sources could be produced. Among different methods for manipulating aerosols, optical trapping stands out due to its flexibility as compared to electrodynamic or acoustic trapping. Manipulation of very small droplets is particularly challenging for the case of acoustic trapping. Optical tweezers are well suited for very small droplets and are readily adaptable to manipulate large numbers of particles. Optical manipulation techniques have been used to trap lasing solid microspheres or lasing droplets emulsified in a host liquid before. Here, we demonstrate lasing from optically trapped liquid aerosols.

We have used a CW infrared laser (1064 nm, 300 mW maximum power) and pulsed green laser (532 nm, 20 ns pulsewidth, 33 kHz repetition rate) for trapping and pumping, respectively. Aerosols were generated using an ultrasonic nebulizer from a 39 % glycerol/water solution doped with 1 mM Rodamine B dye. Nonlinear dependence was observed between the intensity of a whispering gallery mode exhibiting lasing and the pump laser power. Experiments performed with different microdroplet sizes also revealed blue tuning in the average lasing wavelength with decreasing droplet size.

8810-26, Session 6

Light-assisted, templated self-assembly using a photonic-crystal slab *(Invited Paper)*

Eric Jaquay, Luis Javier Martinez Rodriguez, Camilo A. Mejia Prada, Michelle L. Povinelli, The Univ. of Southern California (United States)

The force that light exerts on objects provides tremendous flexibility for trapping and manipulation on the nanoscale. While conventional optical tweezers make use of the optical gradient force arising from a tightly-focused laser beam, recent work has leveraged the strong electromagnetic field gradients near microphotonic devices to manipulate particles. Microphotonic devices such as nanoapertures, plasmonic devices, slot waveguides, microring resonators, and photonic-crystal cavities have all been used for optical trapping. However, such work has largely focused on trapping either single particles or small numbers of particles.

Recently, we have proposed to use optical forces near microphotonic devices for a fundamentally different purpose: to assemble periodic arrays of nanoparticles resembling synthetic, 2D crystals. Our approach, which we call light-assisted, templated self-assembly (LATS), exploits photonic-crystal slabs to create resonantly-enhanced optical forces more than four orders of magnitude larger than radiation pressure. The assembled nanoparticle arrays can be viewed as a form of programmable "optical matter:" by adjusting the wavelength or polarization of the input laser, crystalline structures can be assembled and disassembled in a reconfigurable fashion. Unlike traditional colloidal self-assembly, for which free energy minimization results in hexagonal, close-packed structures, our process is not subject to such constraints. Instead, the use of light to drive the system dramatically alters the underlying potential landscape, allowing for the formation of complex lattices and multiparticle clusters. Here, we provide the first experimental demonstration of the LATS method, assembling a square array of over 100 polystyrene particles in the near field of a silicon photonic-crystal slab.

8810-27, Session 6

High-frequency nano-optomechanics: an exploration at the boundary between photonics, mechanics, and microwaves *(Invited Paper)*

Xiankai Sun, Hong Tang, Yale Univ. (United States)

We will first review recent progress on cavity optomechanics and then talk about our work on integrated nano-optomechanical devices that operate at high frequencies (beyond 1 GHz). Their applications and the directions for future research will also be discussed.

8810-28, Session 6

Single element fiber optic nanomechanical transducers

Donald J. Sirbuly, Ilsun Yoon, Univ. of California, San Diego (United States)

The ability to observe, measure and manipulate individual molecular interactions and mechanical phenomena is central to our understanding of complex chemical pathways and biological processes. Detecting single molecule properties such as conformational changes, intramolecular distances, adhesion forces, or monitoring nanomechanical deformations of cellular components is currently accomplished by using sophisticated techniques such as scan probe technologies and optical/magnetic traps. Although these instruments have excellent resolution it is difficult to scale down the size of the force transducer and feedback mechanism to < 500 nm while maintaining exceptional resolution and multiplexing capability. The development of compact nanomechanical transducers with simple feedback mechanisms could enable a new breed of intracellular probes and technologies for high-throughput nanomechanical analysis. In this talk I will be present some of our recent work on plasmonic nanoparticle coatings embedded in the decaying evanescent field of subwavelength optical waveguides to measure angstrom-level distance changes and sub-piconewton forces. By leveraging the strong plasmon-dielectric coupling effects that occur between the metal nanoparticles and waveguide surface, distances and forces can be extracted with superb sensitivity by simply monitoring the scattering intensity of the nanoparticles or transmission through the fiber. With a fiber geometry, small size, and ability to monitor multiple nanomechanical events with a single optical input, this platform can be directly integrated into microfluidic chips for sensing and high-throughput applications.

8810-29, Session 6

Optical waveguide loop for planar trapping of blood cells and microspheres

Balpreet S. Ahluwalia, Olav G. Hellesø, Univ. of Tromsø (Norway)

An optical waveguide loop with an intentional gap at the center is proposed for planar transport and stable trapping of microspheres/cells. The waveguide acts as a conveyor belt to transport spheres towards the gap. At the gap, the counter-diverging light fields hold the sphere at a fixed position. Depending on the gap separation (2-50 µm) a single or multiple spheres and cells were trapped at the gap. Optical stacking of trapped spheres and cells was also observed experimentally. Numerical simulation based on the finite element method was performed in three dimensions using a computer cluster. The optical force on a single particle was computed for various positions of the particle in the gap. Simulations predicted that a small sphere could be tightly trapped with a precision of ±0.2 µm along the gap exploiting the interference fringes formed in the gap. This was experimentally confirmed on a sphere of 1 µm diameter in 2µm gap separation. Waveguides were made of tantalum pentoxide material and both strip and rib geometries were fabricated. The strip design provides strongly diverging beams (higher trap stiffness) at the gap, whereas rib design allows maneuvering the location of trapped spheres in the gap. The waveguides are only 180 nm thick and thus could be integrated with other functions on the chip, e.g. microfluidics or optical detection, to make an on-chip system for single cell analysis and to study the interaction between cells. The diverging light at the gap can be used to trap and excite Raman scattering.

8810-30, Session 7

Plasmonic nanotweezers based on Au bowtie nanoantenna arrays for manipulation of nano-to-macroscopic objects *(Invited Paper)*

Kimani C. Toussaint Jr., Brian J. Roxworthy, Univ. of Illinois at Urbana-Champaign (United States)

Plasmonic optical traps, or plasmonic "nanotweezers", have emerged as an attractive alternative for optical manipulation because they circumvent the diffraction limit, producing highly confined and enhanced fields that both relax constraints for microparticle manipulation and offer a route for improving nanoparticle trapping. Here, we present an overview of the use of Au bowtie nanoantenna arrays (BNAs) for plasmonic optical trapping. We show that optical absorption by the BNAs creates Rayleigh-Benard convection currents, and that phase-like behavior of trapped particles can be observed. Furthermore, we demonstrate that the adhesion layer material and nanostructure orientation strongly effect trapping behavior. In addition, we discuss the use of a femtosecond-pulsed source in plasmonic nanotweezers and demonstrate that the fs pulses (1) augment the near-field optical forces compared to a comparable, continuous-wave nanotweezers, and (2) increase the diagnostic capabilities of plasmonic nanotweezers by providing access to the nonlinear optical response of trapped species. Finally, we show for the first time that plasmonic nanoantennas are an effective tool for manipulating particles larger than 50 ?m. Using low-numerical aperture illumination (0.25-0.6 NA), we show that manipulation of these "macroscopic" objects is facilitated by increasing the number of illuminated nanostructures participating in the trapping event. Moreover, the increased weight of larger particles makes trapping robust against destabilizing convection forces. These results open up a new pathway for the usage of plasmonic nanotweezers and may have applications for manipulating Eukaryotic cells, studying self-organization/aggregation of cells, and micro-manufacturing.

8810-31, Session 7

Aperture optical trapping of nanoparticles: towards immunoassay and spectroscopy applications

Reuven Gordon, Abhay Kotnala, Ahmed Al-Balushi, Ana Zehtabi-Oskuie, Univ. of Victoria (Canada)

This work will review our recent advances in optical trapping of nanoparticles using the double-nanohole aperture in a metal film. With the double nanohole, we are able to trap nanoparticles in the few nanometer range, including single proteins. We have recently incorporated flow-channel and spectroscopy capabilities into the trapping setup. This has allowed for the monitoring of protein-antibody binding at the single molecule level, and spectroscopic (Raman) identification of the nanoparticle that is trapped. The prospect of this work towards parallel single-protein trapping platforms for immunoassay applications will be presented.

8810-32, Session 7

Measurement of the signal from a single DNA molecule trapped by a nanoplasmonic structure

Jung-Dae Kim, Waleed Muhammad, Yong-Gu Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

Optical tweezers use focused laser to trap microobjects suspended in the medium to the focal point. They are becoming an indispensable tool in microbiology because of its ability to trap tiny biological particles so that single particle analysis is possible. However, it is still very difficult to trap particles such as DNA molecules that are smaller than the diffraction limit. Although trapping of those is possible by increasing the laser power inversely proportional to the cube of the particle diameter, such high power can cause permanent thermal damages. One of the current solutions to this problem is to intensify the local field by the use of the near-field enhancement coming from nanoplasmonic structures illuminated with lasers. Such solution allows one to use low powered laser and still be able to trap them. In this paper, we present the trapping of a single DNA molecule by the use of the strong field enhancement due to a sub-micrometer sized hole drilled on a gold plate by an e-beam milling process and the trapping is verified by the measurement of the scattering signal that comes from the trapped DNA.

8810-33, Session 7

Plasmon-based optical trapping of soft matter nanoparticles

Yasuyuki Tsuboi, Tatsuya Shoji, Hokkaido Univ. (Japan); Hajime Ishihara, Osaka Prefecture Univ. (Japan)

Optical trapping techniques have been extensively investigated as noninvasive and versatile manipulation tools. With a conventional optical tweezer technique using a focused laser beam, micrometer-sized particles involving artificial beads and living cells can be stably trapped and manipulated at a focal point. However, the techniques still have disadvantages for stable trapping toward further smaller nanoparticles. These disadvantages are, that high laser intensity (≥ MW/cm2) is needed to overcome the Brownian motion of nanoparticle, and the spatial resolution in trapping is limited to more than several hundreds of nanometers due to the diffraction limit of incident light.

On the other hand, combination of optical trapping with metallic nanostructure can potentially overcome these disadvantages on the basis of their capability to enhance an electromagnetic field of incident light by a localized surface plasmon (LSP). Plasmonic nanostructures generate much larger trapping forces using relatively lower incident light intensity as compared with that used in conventional optical tweezers.

In the present study, we report such LSP-based optical trapping for organic nanoparticle systems5. In particular, we investigated trapping behavior for soft matter nanoparticles such as an artificial gel and DNA by means of fluorescence microspectroscopy and microscopic real-time video observation. We discovered unique as well as interesting micro-pattern formation in the trapping. We found that photothermal effects simultaneously induced by laser irradiation may play an important role in trapping and micro pattern formation. For desirable optical trapping, it is very important to precisely control these competing three forces.

8810-34, Session 7

Using fluorescence correlation spectroscopy to measure the gradient optical force in an optical tweezers system

André A. de Thomaz, Diogo B. Almeida, Vitor B. Pelegati, Hernandes F. Carvalho, Carlos L. Cesar, Univ. Estadual de Campinas (Brazil)

Gradient optical forces depend on the cubic power of the particle radius, while scattering forces depend on the sixth power of the particle size. Therefore, optical tweezers can only trap particles larger than 40 to 50 nm at room temperature. Below that size Brownian motion fluctuation energy exceeds the trapping potential. Although one cannot trap the particles, the force gradient is still present and could be studied if we managed to measure this force. On the other hand Fluorescence Correlation Spectroscopy [FCS] has been used to observe Brownian motion of single molecules through the excitation focal volume. The autocorrelation curve will change in the presence of a gradient force and could be used to monitor the optical forces even in the no trapping regime. We used an integrated photonic multimodal platform, equipped with both, Optical Tweezers and FCS, to perform a study of the FCS correlation curve of fluorescent beads as a function of trapping force. We observed the correlation spectra as a function of the trapping power and the particle size, in the whole range of no trapping to trapping situations. The Fourier transform of an autocorrelation curve is the power spectrum itself. Interestingly we observed, the typical Fourier Transform power spectra obtained with quadrant detectors of trapped particles for large particles, such as 5 micron diameter beads. We then studied the correlation spectrum for smaller beads, up to the point we could observe the usual diffusion curve for very small particles and low trapping power.

8810-35, Session 7

Enumerating virus-like particles in an optically concentrated suspension by fluorescence correlation spectroscopy

Yi Hu, Ming-Tzo Wei, Xuanhong Cheng, H. Daniel Ou-Yang, Lehigh Univ. (United States)

Fluorescence correlation spectroscopy (FCS) is a sensitive method for enumerating low concentration naoparticles in suspension. However, clinically relevant concentrations are often lower than the FCS detection limit. Feasibility of FCS for enumerating field-enriched nanoparticles involves understanding of the behavior of nanoparticles in the external field. This paper reports an experimental study that combines optical trapping and FCS to examine existing theoretical predictions. Colloidal suspensions of polystyrene nanospheres and HIV-1 virus-like particles are used as model systems. Optical trapping energies and statistical analysis can be used to predict the potential and the limits of FCS for enumerating optically concentrated nanoparticles.

8810-36, Session 7

Volume phase transition of polymer gel induced by plasmonic optical trapping with infrared light radiation

Kosei Ueno, Sho Nozawa, Hiroko Itoh, Wakako Nakano, Hiroaki Misawa, Hokkaido Univ. (Japan)

Closely-spaced gold nanochain structures whose plasmon resonant wavelength is far-infrared region were fabricated by electron beam lithography and lift-off techniques. To induce volume phase transition of polymer gel owing to radiation force working on nanogap, poly(N-isopropylacrylamide)-sodium acrylate (PNIPAM-SA) co-polymer gel was deposited on the closely-spaced gold nanostructures and subsequently femtosecond or continuous wave (CW) laser beam (10 μm (30 THz) or 10.6 μm (28.3 THz)) was irradiated on the gold nanostructured substrate. When the PNIPAM-SA co-polymer gel was placed on closely-spaced gold nanoparticles and subsequently laser beam was irradiated on them, the volume phase transition of polymer gel was clearly observed even with an irradiation power of 0.1 kW/cm2 under the incident polarization parallel to the nanochain structure. On the other hand, we have confirmed that the volume phase transition of polymer gel was not observed under the incident polarization perpendicular to the nanochain structure. Therefore, we conclude that the volume phase transition of polymer gel was induced since the balance of the osmotic pressure in polymer gel collapsed due to intense radiation force at nanogap. In this system, however, there is a possibility that the volume phase transition was induced by the rise in heat on gold nanostructures based on the plasmon excitation. Therefore, we are trying to perform analogous experiments using polyacrylamide gel which does not effect on temperature and possibility for the infrared sensor.

8810-37, Session 8

Information and thermodynamics: experimental verification of Landauer's erasure principle *(Invited Paper)*

Antoine Bérut, Artyom Petrosyan, Sergio Ciliberto, Ecole Normale Supérieure de Lyon (France)

Rolf Landauer argued that the erasure of information is a dissipative process. A minimal quantity of heat, proportional to the thermal energy, is necessarily produced when a classical bit of information is deleted. A direct consequence of this logically irreversible transformation is that the entropy of the environment increases unavoidably by a finite amount. We experimentally show the existence of the Landauer bound in a

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generic model of a one-bit memory. Using a system of a single colloidal particle trapped in a modulated double-well potential, we establish that the mean dissipated heat saturates at the Landauer bound in the limit of long erasure cycles. This result demonstrates the intimate link between information theory and thermodynamics. For a memory erasure procedure, which is a logically irreversible operation, a detailed Jarzynski Equality is verified, retrieving the Landauer limit independently of the work done on the system.

8810-38, Session 8

Particle dynamics and thermodynamics in a virtual potential

John Bechhoefer, Momcilo Gavrilov, Yonggun Jun, Simon Fraser Univ. (Canada)

Feedback, or ABEL traps can create arbitrary virtual potentials for exploring the dynamics of small Brownian particles. In a feedback trap, the particle position is measured periodically and, after each measurement, one applies the force that would be produced by the gradient of the “virtual potential” that is imposed at the particle location.

Virtual potentials differ from real ones in that the feedback loop introduces dynamical effects not present in ordinary potentials. These dynamical effects are caused by small time scales associated with the feedback. The time scales include the delay between the measurement of a particle’s position and the feedback response, the feedback response that is applied for a finite update time, and the finite camera exposure from integrating motion.

Here, we present detailed theoretical, simulation, and experimental studies of the dynamics (power spectra, correlation function) and thermodynamics (work, heat) of a particle in a virtual harmonic potential with constant and time-dependent stiffness. We show that deviations from the behavior in a continuous potential are measured by the ratio of these small time scales to the relaxation time scale of the virtual potential. From the understanding we gain, we can explore the thermodynamics of particles in an arbitrary time-dependent potential. A first application of such ideas is to measure the thermodynamic cost of information erasure in double-well potentials.

8810-39, Session 8

Frustration effects and grain boundaries in colloidal particle orderings on optical substrates

Danielle McDermott, University of Notre Dame (United States); Andras Libal, Univ. Babes-Bolyai (Romania); Gia-Wei Chern, Charles M. Reichhardt, Cynthia J. Olson Reichhardt, Los Alamos National Lab. (United States)

We propose that a system of colloidal particles interacting with a honeycomb array of optical traps that each contain three wells can be used to realize a fully packed loop model. One of the phases in this system can be mapped to Baxter’s three-coloring problem, offering an easily accessible physical realization of this problem. As a function of temperature and interaction strength, we find a series of phases, including long range ordered loop or stripe states, stripes with sliding symmetries, random packed loop states, and disordered states in which the loops break apart. For square arrays of traps that each contain two wells, a spin ice state can be realized, and using colloidal particles, we show that it is possible to produce dynamical ice defects by creating multiply occupied or unoccupied traps. Our geometries could be constructed using ion trap arrays, BEC vortices in optical traps, or magnetic vortices in nanostructured superconductors.

8810-40, Session 8

Soft spots and light-force induced rearrangements in colloidal glasses *(Invited Paper)*

Arjun G. Yodh, Ye Xu, Tim Still, Univ. of Pennsylvania (United States); Kevin B. Aptowicz, West Chester Univ. of Pennsylvania (United States); Matt Gratale, Univ. of Pennsylvania (United States)

I will describe recent work which explores the connections between particle dynamics and mechanical response of disordered media. For example, we have experimentally studied the phonon modes [1,2] of disordered colloidal packings, and the role played by particular low-frequency quasi-localized phonon modes (“soft spots”) in driving particles to rearrange in response to compressive stress [3]. Our colloidal suspensions are composed of temprature-sensitive hydrogel particles, made from cross-linked poly(N-isopropyl acrylamide). By varying sample temperature, the colloid packing fraction is varied. Using video microscopy and particle tracking techniques, vibrational modes are derived from particle displacement correlations. New experiments that study correlations between the modes and the particle rearrangements due to laser-tweezer/thermally induced stresses will also be described.

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8810-41, Session 8

Resonances arising from hydrodynamic memory: the color of Brownian motion

Sylvia Jeney, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Observation of the Brownian motion of a small probe interacting with its environment is one of the main strategies to characterize soft matter. Initially, the particle is driven by rapid collisions with the surrounding solvent molecules, referred to as thermal noise. Later, the friction between the particle and the viscous solvent damps its motion. Conventionally, thermal force is taken to be characterized by a Gaussian white noise spectrum. The friction is assumed to be given by the Stokes drag, suggesting that motion is overdamped at long times, when inertia becomes negligible.

Recently, we measured the noise spectrum of the thermal forces by tracking with high resolution a single micron-sized sphere suspended in a fluid, and confined by a stiff optical trap. Coupling between sphere and fluid gives rise to hydrodynamic memory and a resonance, equivalent to a colored peak in the power spectral density of the sphere’s thermal fluctuations. Our results reveal that motion is not overdamped, and the particle-fluid-trap system can be considered a nanomechanical resonator.

By bridging novel theoretical insights to model experiments with unprecedented accuracy, we are aiming at developing a novel type of multidimensional, time-resolved, near-field sensor for the study of soft and living matter.

8810-42, Session 9

Self-driven particles on asymmetric trap arrays

Lena M. Lopatina, Charles M. Reichhardt, Cynthia J. Olson

Reichhardt, Los Alamos National Lab. (United States)

In this work we propose a new way to manipulate active swimmers, such as bacteria or artificial swimmers. Self-propulsion, which is the main feature of active matter, produces a unique spectrum of novel properties in active matter. Previous research has been concentrated in the areas of extracting work from bacteria [1], sorting self-propelled particles/bacteria [2], and flocking, in which the addition of interactions between particles/bacteria leads to the formation of correlated groups/flocks [2].

In our work we demonstrate a new feature of self-propelled particles and bacteria - self-organization caused solely by self-propulsion, without any additional interactions in the matter. By means of computer simulations, we study how the density of swimmers affects this self-organization. Then, we show how, by placing just one additional object into the media, we can enhance the self-organization drastically. In addition to studying the phase diagram, we investigated how one can describe the system by measuring visually observable signals. This research will lead to a better understanding of the properties of the bacteria and artificial swimmers, which will lead to the development of new sensor technologies.

[1] A. Sokolov et al, PNAS, vol. 107, p. 969, 2010

[2] J. Drocco et al, Proc. SPIE 8458, Optical Trapping and Optical Micromanipulation IX, 84581, 2012

8810-43, Session 9

Real-time calcium measurements of live optically trapped microorganisms

Charlie Chandsawangbhuwana, Linda Z. Shi, Qingyuan Zhu, Michael W. Berns, Univ. of California, San Diego (United States)

A system has been developed that allows for the real-time measurement of calcium dynamics in swimming sperm. Specifically, the ratiometric dye Indo-I is used as a fluorescent indicator of intracellular calcium dynamics. The dual emissions are collected by a high-sensitivity back-illuminated CCD camera coupled to a Dual-View imaging system. From the CCD, the images are sent to a custom developed algorithm which processes the images and outputs the calci-um measurements in real-time. Additionally, sperm velocity and position data are processed and outputted in real-time. The velocity and position data are obtained using a separate coupled red light (>670 nm) phase contrast imaging setup that does not optically interfere with the fluorescent imaging. Using this system the effects of optical trapping on calcium dynamics was determined.

8810-44, Session 9

Optically-driven swimmers

Vincent L. Y. Loke, Alexander B. Stilgoe, Daryl C. Preece, Timo A. Nieminen, Halina Rubinsztein-Dunlop, The Univ. of Queensland (Australia)

Non-axisymmetric microstructures, immersed in a liquid, can be rotationally driven in optical trap. These objects can be either chiral or non-chiral. The chiral structures, due to its symmetry, potentially couples rotational fluid flow to translational fluid flow to produce thrust in the direction of its axis. An ideal optically driven swimmer exploits both optical torque and fluid flow to achieve swimming motion.

We investigate number of structures for their suitability as optically-driven swimmers. They take the form of helical, turbine or propeller-like structures. Theoretical models are used to aid the design of such structures. The optical forces and torques are calculated using a combination of discrete dipole approximation and the T-matrix method. Forces due to fluid flow are determined by solving Laplace's equation via the finite element method or other means.

Working in the low Reynolds number regime, the Scallop theorem predicts that any deformation of the swimmer must not be invariant under time reversal. On that score, a chiral structure, with no moving parts but rotating on its own axis, would be a suitable swimmer; it can also be used as a pump when held in place by a highly converging beam.

In conjunction with the results from the theoretical models, the optically-driven swimmers can be prototyped using two-photon photo-polymerization. This is a process where a receptacle containing resin is raster-scanned in 3D on a movable stage; the resin is selectively cured at the required coordinates. The uncured portion is washed away leaving the desired microstructure which can then be manipulated using optical tweezers. Optical forces and torques are subsequently measured.

8810-45, Session 9

Hydrodynamic synchronisation of rotating spheres

Simon Hanna, Luke J. Debono, Stuart J. Box, David B. Phillips, Stephen H. Simpson, Univ. of Bristol (United Kingdom); Nicolas Bruot, Jurij Kotar, Pietro Cicuta, Univ. of Cambridge (United Kingdom)

Hydrodynamic coupling is thought to play a role in the coordinated beating of cilia and flagella, and may inform the future design of artificial swimmers and pumps. In this study, holographic optical tweezers are used to investigate the hydrodynamic coupling between a pair of driven oscillators. The theoretical model of Lenz and Ryskin [1] is experimentally recreated, in which each oscillator consists of a sphere optically driven in a circular trajectory. The optical trap position is maintained ahead of the sphere to provide a tangential driving force. The trap is also moved radially to harmonically constrain the sphere to the circular trajectory. Analytically, it has been shown that two oscillators of this type are able to synchronize or phase-lock under certain conditions [2, 3]. We explore the interplay between synchronization mechanisms and find good agreement between experiment, theory and Brownian dynamics simulations.

[1] P. Lenz and A. Ryskin, Physical Biology 3, 285–294 (2006).

[2] T. Niedermayer, B. Eckhardt, and P. Lenz, Chaos 18, 037128 (2008).

[3] N. Uchida and R. Golestanian, Physical Review Letters 106, 058104 (2011).

8810-46, Session 9

Photonic force based investigations of filopodial dynamics

Felix Kohler, Alexander Rohrbach, Albert-Ludwigs-Univ. Freiburg (Germany)

Filopodia are needle-like highly dynamic cellular protrusions, which play an important role in many essential cellular processes like cell adhesion, cell migration, wound healing and phagocytosis. Filopodia constitute one of the most isolated substructures of a cell. These finger-like highly dynamic cell protrusions provide a system at an interesting level of complexity. However, only little is known about the mechanical properties and the dynamics of cellular subsystems like filopodia.

The exposed location of filopodia at the cellular surface makes these structures easily accessible for optical tweezers based cellular investigations. We use photonic force microscopy to investigate the mechanical concepts of filopodial dynamics during phagocytosis. Therefore, an optically trapped bead is attached to a filopodium. The fast and precise motion tracking of the bead reveals important information about the underlying mechanics driving the motion. The analysis of the mean displacement of the bead allows the determination of the velocities and forces that appear during the filopodial retraction as well as during the transport of a bead along a filopodium. It could be revealed that filopodia often show a spasmodic kind of retraction with intervals of fast and slow motions. This behavior helps to better understand the discrepancies between the reported filopodial retraction velocities that are based on measurements of different timescales. By means of the analysis of the beads fluctuations, various processes like the binding of the bead to the cell membrane, the possible release of a clutch and the arrival of the bead at the cell body could be identified.

8810-47, Session 10

Tutorial: studying single molecules with sub-nanometer precision: a review of techniques and applications *(Invited Paper)*

Thomas T. Perkins, National Institute of Standards & Technology (United States) and Univ. of Colorado (United States)

A specially commissioned review of high-precision optical trapping measurements for application to single molecule biophysics, in advance of publication of an Annual Review of Biophysics article on the subject.

8810-48, Session 10

Single molecule manipulation experiments: theory, analysis, interpretation *(Invited Paper)*

Olga Dudko, Univ. of California, San Diego (United States)

Single-molecule manipulation tools are making it possible to measure the response of individual biomolecules to external force - in real time and with unprecedented resolution - revealing information that is typically lost when studied though traditional "bulk" methods. I will present a general analytical theory of force-induced molecular transitions. The applications of the theory will be illustrated with data from single-molecule pulling experiments on (i) unfolding of riboswitches and (ii) unbinding of a receptor-ligand complex involved in blood clot formation with optical tweezers, (iii) unzipping of individual DNA hairpins with nanopores, and (iv) unfolding of proteins with an atomic force microscope.

8810-49, Session 11

Ultrafast force-clamp laser trapping of single molecular motors and DNA binding proteins

Marco Capitanio, Carina Monico, Francesco Vanzi, Francesco S. Pavone, Univ. degli Studi di Firenze (Italy)

Force plays a fundamental role in a wide array of biological processes, regulating, for example, enzymatic activity, kinetics of molecular bonds, and molecular motors mechanics. Single molecule force spectroscopy techniques have enabled the investigation of such processes, but they are inadequate to probe short-lived (millisecond and sub-millisecond) molecular complexes. Here, we present a novel force-clamp laser trap that is capable of applying constant loads to molecular complexes with lifetimes above ~10 μs [Capitanio et al., Nature Methods 9, 1013-1019 (2012)]. Such capability is enhanced by a detection strategy allowing the investigation of very short interactions (~100μs). Moreover, the high temporal and spatial resolution of the method enables us to probe sub-nanometer conformational changes with a time resolution of few tens of microseconds. We tested our method on molecular motors and DNA-binding proteins. We applied constant loads to a single motor domain of myosin before its working stroke was initiated (0.2–1 ms), thus directly measuring its load dependence. We found that, depending on the applied load, myosin weakly interacted (<1 ms) with actin without production of movement, fully developed its working stroke or prematurely detached (<5 ms), thus reducing the working stroke size with load. These results resolve the molecular mechanism underlying regulation of muscle contraction by force. Our technique could be straightforwardly applied to a wide variety of non-processive molecular motors, single domains of processive motors, protein-DNA and protein-RNA interactions, and conceivably to any short-lived protein-protein interaction, opening new avenues for investigating the effects of forces on biological processes.

8810-50, Session 11

Dynamic single-molecule force spectroscopy using optical tweezers and nanopores

Nadanai Laohakunakorn, Univ. of Cambridge (United Kingdom); Sebastian Sturm, Univ. Leipzig (Germany); Oliver Otto, Technische Univ. Dresden (Germany); Ulrich F. Keyser, Univ. of Cambridge (United Kingdom); Klaus Kroy, Univ. Leipzig (Germany)

Single-molecule force spectroscopy is a powerful technique for studying the detailed behaviour of biopolymers such as DNA and proteins. It takes advantage of tools such as the atomic force microscope and optical tweezers to apply pN-scale forces to individual molecules. The resulting response of the molecule enables properties such as conformations, folding pathways, and intermolecular interaction strengths to be determined. Traditionally these studies have been carried out under static tension. The dynamic response of polymers to a sudden change in force is experimentally more challenging as the polymer is often coupled to an external molecular handle, which suppresses important physics at short (~ms) timescales. Here we use a nanopore to electrically control the application of force to the end of a double-stranded DNA molecule; the other end of the molecule is attached to a bead held in an optical trap. By shutting off the voltage, the fast relaxation dynamics of the free polymer end can be studied. We observe for the first time an enhanced viscous friction which arises from the rapid internal contraction of the DNA, which is fully explained by theory. These studies pave the way for new dynamic force-spectroscopy experiments, such as investigations of tension propagation along biomolecules, which has applications for both polymer theory as well as biological systems such as the cytoskeleton where dynamic tension can affect cellular response.

8810-51, Session 11

Why soft UV A damages DNA: a laser microbeam study

Karl Otto Greulich, Fritz Lipmann Institute (Germany); Alexander Rapp, Technische Univ. Darmstadt (Germany)

Laser microbeam studies have solved a puzzle on DNA

damage and repair (1). Such knowledge is crucial for understanding cancer and ageing. So far it was not understood, why the soft UV component of sunlight, UV A, causes the dangerous DNA double strand breaks. The energy of UV A photons is below 3.5 eV, too low to directly cleave the corresponding chemical bonds in DNA. This is occasionally used to claim that artificial sunbeds, which mainly use UV A, would not impose a risk on health.

UV A is in a first step sufficient only for single strand breaks. The essential new observation is that, when on the opposite strand there is an other single strand break at a distance of up to 20 base pairs, these two breaks will be converted into a break of the whole double strand with all its known consequences for cancer and ageing.. However, in natural sun the effect is counteracted (2). Simultaneous red light illumination reduces UV induced DNA damages to 1/3. Since sunlight has a red component, skin tanning with natural sun is not as risky as might appear at a first glance.

1 R. Greinert, B. Volkmer, S. Henning, E.W. Breitbart, K.O. Greulich, M.C. Cardoso and A. Rapp 2012 Nucl Acids Res , 1 - 11 doi 10.1093/nar/gks824

2 A. Dube, C. Bock, E. Bauer, R. Kohli, P. Gupta and K. O- Greulich 2001 Rad Env Bioph 40, 77 - 82

8810-52, Session 11

Magnetic trapping of single molecules: principles, developments, and applications *(Invited Paper)*

Terence R. Strick, Ctr. National de la Recherche Scientifique (France)

Magnetic trapping provides a robust and highly parallelizable means for isolating and manipulating single biopolymers such as DNA, RNA and proteins. Here we will discuss basic principles of magnetic trapping; compare and contrast optical trapping and magnetic trapping for biomolecular applications; review recent developments in magnetic trapping approaches; and discuss the use of magnetic trapping for the study of complex, multicomponent biological reactions -- in particular for the analysis of DNA repair.

8810-53, Session 11

Probing ribosomal protein-RNA interactions with an external force *(Invited Paper)*

Pierre Mangeol, Mathilde Bercy, Ecole Supérieure de Physique et de Chimie Industrielles (France); Thierry Bizebard, Claude Chiaruttini, Marc Dreyfus, Mathias Springer, Institut de Biologie Physico-Chimique (France); Ulrich Bockelmann, Ecole Supérieure de Physique et de Chimie Industrielles (France)

Ribosomal (r-) RNA is well structured in the ribosome, but the role of r-proteins and enzymes in the assembly process is poorly understood. We address this question by using optical tweezers to unfold RNA fragments in the presence or absence of proteins.

We first studied the case of Escherichia coli L20, an early binding r-protein, whose globular C-terminal domain (L20C) recognizes the essential 991-1163 subdomain of the 23S rRNA. We found that L20C makes RNA fragments surrounding its binding sites more resistant to mechanical unfolding. The points of increased resistance coincide within two base pairs with the binding sites identified by conventional methods. Comparing unfolding and refolding traces and including studies with mutated RNA, we found that L20C acts as a clamp and not as a RNA chaperone.

Recent biochemical experiments in E.Coli indicate that SrmB, a DEAD-box protein that shows RNA helicase activity in the presence of ATP, assists ribosome assembly by favoring the in vivo folding of the 991-1163 subdomain. We are now trying to reproduce this effect in vitro with the optical tweezers and are extending the work to the other r-proteins that contact the same subdomain.

Related publication:

P. Mangeol, T. Bizebard, C. Chiaruttini, M. Dreyfus, M. Springer and U. Bockelmann, Proc. Natl. Acad. Sci. 45, 18272 (2011).

8810-54, Session 12

Active fluctuations of chromosomal DNA in E. Coli in vivo

Rudra P. Kafle, Jens-Christian D. Meiners, Univ. of Michigan (United States)

In E Coli, the genome is tightly compacted in a nucleoid of less than a cubic micron. The conformation of the DNA undergoes large- and small-scale changes during the life cycle of the cell, enabling replication, transcription, and the formation of highly specialized DNA-protein complexes that control biological processes.

The dynamics in the nucleoid are subject to a multitude of constraints, forces, and fluctuations. We study the conformational fluctuations of chromosomal DNA in live and dead Escherichia Coli cells by Fluorescence Correlation Spectroscopy (FCS) on in vivo labeled DNA, yielding the displacement of the DNA on time scales from microseconds to seconds and the corresponding viscoelastic properties of the nucleoid. We observe a substantial decrease in the displacement fluctuations in dead cells, compared to the live cells. The larger fluctuations in the living cells may indicate that they are driven by active processes involving molecular motors that generate forces by ATP hydrolysis. On shorter time scales, we see a little difference between live and dead cells, suggesting that faster processes rely primarily on thermally-driven diffusive mechanisms.

We interpret these data in comparison to in-vitro measurements with optical tweezers in which we have simulated the effect of motor-driven fluctuations by shaking the end of the DNA and measure the rate of protein-mediated DNA loop formation. Small additional fluctuations can substantially enhance these rates, suggesting that motor-driven intracellular noise may be critical to efficient cellular function.

8810-55, Session 12

On the fundamentally soft nature of the bacterial chromosome *(Invited Paper)*

Suckjoon Jun, Univ. of California, San Diego (United States)

Replicating bacterial chromosomes continuously demix from each other and segregate within a compact volume inside the cell called the nucleoid. Although many proteins involved in this process have been identified, the nature of the global forces that shape and segregate the chromosomes has remained unclear because of limited knowledge of the micromechanical properties of the chromosome. In the shorter first half of this talk, I will summarize the physics of polymer in confined space. In the second part, I will describe our recent experimental work that shows the bacterial chromosome in confined space remarkably behaves as a loaded entropic “spring”. In particular, comparison with the viral DNA in a capsid reveals the fundamentally soft nature of the bacterial chromosome.

8810-56, Session 12

Optical trapping of T cells

Amanda J. Wright, The Univ. of Nottingham (United Kingdom); David Glass, Niall McAlinden, Owain R. Millington, Univ. of Strathclyde (United Kingdom)

Since the first optical trap was reported in the late 1970s it has been shown to be a hugely versatile tool when it comes to biological applications and Life Science research. As the number of applications increases and the optical trapping technology becomes more advanced there is an increasing need to be able to perform accurate, quantitative experiments that directly trap the cell of interest without the need to introduce exogenous beads into the sample. The issue with trapping cells directly is that they are often larger than beads and are distinctly non-uniform with widely varying refractive indices. This has practical implications in terms of trapping the cell as a whole rather than just a small feature of the cell, preventing the cell from re-orientating during experiments and, most importantly, performing reliable measurements on the sample and cell which most often involve accurately tracking the cell’s position. We will present a series of experiments and mathematical models that aim to address these issues, highlighting novel beam shapes that can be used to trap the cell as a whole and fluorescent imaging techniques that allowing accurate cell position tracking. Our interest is in optically trapping T cells, which are part of the immune system, although the approaches presented are not limited to T cells and could easily be adapted to suit the sample of interest. Using the techniques developed we demonstrate how optical tweezers can be used probe the dynamic interactions that occur between cells in the adaptive immune system.

8810-57, Session 12

Contributions of actin and myosin to creep compliance of blood stem cells during differentiation

Andrew E. Ekpenyong, Technische Univ. Dresden (Germany); Graeme B. Whyte, Kevin J. Chalut, Stefano Pagliara, Lars Boyde, Chii J. Chan, Franziska Lautenschläger, Ulrich F. Keyser, Univ. of Cambridge (United Kingdom); Jochen R. Guck, Univ. of Cambridge (United Kingdom) and Technische Univ. Dresden (Germany)

Stem cells modulate their mechanical properties during differentiation. We recently showed that during the differentiation of hematopoietic stem and precursor cells into three different myeloid lineages, the cells alter their mechanical properties to suit their ultimate fates and functions. Although the mechanical properties of cells are largely determined by the cytoskeleton, how such properties derive from cytoskeletal details is still largely unclear.

Here, we show the relative contributions of filamentous actin and myosin II to cell compliance, measured with a microfluidic optical stretcher. Pharmalogical interventions using Cytochalasin D and Blebbistatin specifically disrupt the actin and myosin II components of the cytoskeleton, respectively. By monitoring the creep compliance of cells from induction of differentiation up to the emergence of fully differentiated cells, alongside these pharmacological interventions, we simultaneously quantified the changes in cellular mechanical properties due to differentiation and acto-myosin depolymerization.

Our results indicate that while all three mature lineages can be distinguished from the undifferentiated cells and from one another based on the creep compliance, the relative contributions of actin and myosin II are nearly constant and lineage-independent. Actin depolymerization leads to a significant increase in creep compliance while myosin II disruption engenders a significant decrease in creep compliance, for primary human cord blood derived hematopoietic stem cells (CD34+), cell line precursor cells (HL60) and all their differentiated lineages (neutrophils, monocytes and macrophages). In line with our earlier work showing the function-specificity of cell mechanical properties, the present results adumbrate the biomolecular basis of cellular mechanical properties.

8810-58, Session 12

New biodiagnostics based on optical tweezers: sub-typing red blood cells, and identification of drug resistant bacteria *(Invited Paper)*

Jia-Wen Chen, Feng Yuan Hospital (Taiwan); Chuen-Fu Lin, Shyang-Guang Wang, Yi-Chieh Lee, Chung-Han Chiang, Min-Hui Huang, Central Taiwan Univ. of Science and Technology (Taiwan); Yi-Hsiung Lee, Feng Chia Univ. (Taiwan); Guy Vitrant, IMEP-LAHC (France); Ming-Jeng Pan, Central Taiwan Univ. of Science and Technology (Taiwan); Horng-Mo Lee, Central Taiwan University of Science and Technology (Taiwan); Patrice L. Baldeck, Ctr. National de la Recherche Scientifique (France) and Central Taiwan Univ. of Science and Technology (Taiwan); Chih-Lang Lin, Central Taiwan Univ. of Science and Technology (Taiwan)

It has been previously demonstrated that optical tweezers forces on biological micro-objects can be used to develop innovative biodiagnostics methods. In the first part of the presentation, we present a new sensitive method to determine A, B, D types and subtype of red blood cells. Target antibodies are coated on glass surfaces. Optical forces needed to drag RBC from the glass surface increase when RBC antigens interact with their corresponding antibodies. Antibody dilutions are used to determine their interaction strengths with RBCs. We demonstrate that the sensitivity of this method is 16-folds higher than the agglutination method. Furthermore, the difference in sensitivity can be used to distinguish the major RBC types and subtypes.

In the second part, we present an original way to measure in real time the wall thickness of bacteria, that is one of the most important diagnostic parameters of bacteria drug resistance. In hospital diagnostics, it is still measured by TEM which is time consuming for critical diagnostics. We have found that the wall thickness of shell bacterias is directly proportional to their optical forces. After calibration with known bacteria, the method has been succefully applied to indentify, from blind tests, methicillin-resistant staphylococcus aureus, including VSSA (NETC 10442), VISA (Mu 50), and heto-VISA (Mu 3).

8810-59, Session 13

Evaluating cell matrix mechanics using an integrated nonlinear optical tweezer-confocal imaging system

Berney Peng, Tufts Univ. (United States); Carlo-Amadeo C. Alonzo, Tufts Univ (United States); Irene Georgakoudi, Mark Cronin-Golomb, Tufts Univ. (United States)

Studies have demonstrated that biophysical effects such as extracellular matrix (ECM) stiffening and remodeling can drive cancer progression and metastatic potential. As such, the ability to make microscale rheology measurements coupled with simultaneous optical imaging in 3D cultures can be critical when monitoring these physiological processes for mechanistic understanding. This paper describes the inclusion of optical tweezers based microrheology in a microscope that had been designed for nonlinear optical imaging of collagen networks in ECM. We show preliminary results using mammary gland epithelial cells.

8810-60, Session 13

Probing multiscale mechanics of collagen with optical tweezers

Marjan Shayegan, Naghmeh Rezaei, Benjamin P. B. Downing, Andrew Wieczorek, Nancy R. Forde, Simon Fraser Univ. (Canada)

Mechanical response is a key property of many types of materials, yet rational design of mechanical response remains an enormous challenge. By studying the mechanics of collagen, the fundamental structural protein in vertebrates, and how these are altered by changes in chemical composition, we hope to provide insight into the interplay between chemistry and mechanics. Because collagen is a self-assembling protein, we are characterizing its mechanics at various stages in its hierarchical assembly pathway, to provide insight into how they can be altered at different structural levels in aging, in disease, and in desirable ways to develop new biomaterials.

We have built optical tweezers instruments to manipulate and measure forces acting on microspheres, which we use either as handles to stretch single molecules of collagen, or as probes of the local viscoelastic environment in microrheology experiments. Because of collagen's relatively short length, care must be taken that forces measured in single-molecule stretching experiments reflect the behaviour of the tethered molecule, which we address through quantification of physical interactions and introduction of specific chemical labels. In microrheology experiments, we observe that collagen's chemical composition influences the dynamics and strength of interactions between collagens, which we quantify with simple viscoelastic models. We furthermore probe the development of mechanical heterogeneity at the microscale as collagen undergoes self-assembly into fibrillar networks.

8810-61, Session 13

Optical stretching of lipid bilayer membranes in dual beam optical trap

Roshni Biswas, Mehmet Solmaz, Shalene Sankhagowit, Camilo A. Mejia Prada, Noah Malmstadt, Michelle L. Povinelli, The Univ. of Southern California (United States)

The elastic deformation of lipid bilayer membranes underlies many basic physiological processes. Accurate techniques for measuring the bending modulus of lipid bilayers can thus yield crucial insight into membrane biology. Giant unilamellar vesicles (GUVs), spherical objects consisting of a single lipid bilayer, form a common model for probing membrane mechanics. In this work, we use a dual beam optical trap (DBOT) to trap and stretch GUVs. When trapped, the GUVs assume the shape of a prolate spheroid with an eccentricity that depends on the trapping power and the intrinsic elasticity, or bending modulus, of the GUV's lipid membrane. The bending modulus is extracted from the applied optical stress and resulting surface area strain. In our experiments, we analyzed two populations of GUVs with membranes composed of distinct lipids, one in liquid phase (POPC) and the other in gel phase (DPPC). It is expected that the bending modulus of the lipid in liquid phase will be substantially lower than that in the gel phase, and this fact is validated in our experiment. We also analyzed the effect of adding cholesterol to lipid membranes. We expect that the high-throughput, flow-through nature of the DBOT setup will allow the convenient collection of data on large numbers of GUVs, e.g. with varying size, composition, and/or biochemical environment. In this manner, this platform may also provide a method for quantifying the response of membrane mechanical properties to small molecules, drugs, nanoparticles, and other agents.

8810-62, Session 13

Optical manipulation of vesicles for optofluidic applications

Andreas E. Vasdekis, Ecole Polytechnique Fédérale de Lausanne (Switzerland) and Pacific Northwest National Lab. (United States); Evan A. Scott, Jeffrey A. Hubbell, Demetri Psaltis, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

In this talk, we will review our recent results in the optical manipulation of vesicles [1, 2]. We will first discuss more traditional approaches in vesicle manipulation using optical tweezers, which have enabled a wide range of vesicle studies, such as their dynamic manipulation, as well the study of their mechanical properties [2, 3]. We will then focus on our present work, which is based on utilizing the photon energy, rather than its momentum. Polymersomes, vesicles synthesized from block-copolymers, were sensitized by adding an oxidizing moiety on their membrane. The later converts incident photons to reactive oxygen species. This latter step enabled the complete destabilization of the vesicles and release of their contents under optical excitation, involving both coherent and incoherent radiation. Short light exposures lead to polymersomes re-organization into smaller diameter vesicles. Extended illumination leads to complete destabilization, and micelle formation. Single particle analysis revealed payload release takes place within seconds of illumination in an explosive burst. We will discuss the destabilization and payload release kinetics, as revealed by microscopy at the single particle level, and will end with applications including single cell biomodulation, as well as an outlook for future potential applications in optofluidics.

[1] A. E. Vasdekis, E. A. Scott, D. Psaltis, J. A. Hubbell, ACS Nano 6, 7580 (2012).

[2] A. E. Vasdekis, E. A. Scott, J. A. Hubbell, D. Psaltis, Annual Review of Materials Research, accepted (2013).

[3] P. M. Bendix, L. B. Oddershede Nano Lett. 11, 5431 (2011).

8810-63, Session 13

The influence of myosin-generated force to the intracellular microrheology in living cells

Ming-Tzo Wei, H. Daniel Ou-Yang, Lehigh Univ. (United States)

The mechanics of biological cells are governed by a network of cytoskeletal filaments and molecular motors forming a dynamic mechanical entity. A recent experimental study by Mizuno et al. showed that local shear modulus of a synthesized cytoskeletal network could increase as a result of myosin-generated internal stresses. To examine whether similar behaviors could take place in living cells we combined active and passive microrheology to measure the myosin-generated fluctuating force and intracellular shear modulus in HeLa cells. While our experiment did show an increase in the fluctuations of the shear modulus with increasing motor forces, the experiment did not find a direct correlation between the mean intracellular shear modulus and the motor-generated fluctuating force. Based on Mizuno et al's assumption that shear modulus is an increasing function of the local tension, the difference between the results obtained by the intracellular behavior and that obtained from the synthesized cytoskeletal network could be due to the existence of a steady-state intracellular tension that is stronger than the motor-generated fluctuating force. Unfortunately, our experimental method could measure only the fluctuating forces but not the steady-state tension in the system. Further studies that measure both fluctuating and steady-state forces at the same time may be required to address this problem.

8810-64, Session 14

Rotational optical microrheology of liquid interfaces

Matthieu Robert de Saint Vincent, Yoshihiko Arita, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Complex interfaces are involved in many fields related to biological materials (cell membrane properties…), industrial processes (foam and emulsion stability, oil recovery…) as well as basic two-phase fluid dynamics problems. They indeed exhibit specific two-dimensional rheological properties which strongly influence macroscopic behaviour, and have motivated intensive research efforts over the past decades.

A popular approach to determine the interfacial shear viscosity of adsorbed monolayers consists in measuring the torque induced on a macroscopic rotating disk straddling the interface to be probed, which results from both contributions of bulk phases and monolayer. In this context, reducing the probe size benefits from a favourable scaling behaviour, therefore allowing for an enhanced sensitivity.

We propose a top-down version of this approach, where a birefringent particle straddling a liquid-liquid interface is set into rotation by a circularly-polarized laser beam in an optical trap. Such micrometre-scale rotating particle can indeed be viewed as equivalent to a scale-reduction of the rotating disk by four orders of magnitude. By simultaneously measuring the optical torque exerted upon the trapped particle and the resulting rotation rate, we can probe the surface shear viscosity of surfactant monolayers covering the interface. Viscosities within the 10-7 Pa s m range have thus been successfully measured at water-oil interfaces.

This high sensitivity, together with a high spatial selectivity, make this approach very promising for characterizing a wide range of inhomogeneous soft interfaces at the micron scale.

8810-65, Session 14

Oscillating droplets in optical traps

Stephen H. Simpson, Rory M. Power, Jonathan P. Reid, Univ. of Bristol (United Kingdom)

We report on the application and analysis of a powerful and novel form of viscometry, capable of measuring viscosities over a range of twelve decades. The technique relies on the use of holographic optical traps to induce coalescence between pairs of liquid micro-droplets. Immediately following such an event, the newly formed droplet undergoes shape oscillations whose evolution is determined by its physical properties. We show, using a combination of experiment and simulation, how this process can be monitored optically and describe how the liquid viscosity can subsequently be evaluated. In particular we present a detailed numerical analysis of light scattering from oscillating droplets. Two main observations are made. First of all, characteristic patterns of morphological resonances are observed for independent oscillation modes. The conditions for these resonances are shown to provide an accurate measure of particular dimensions of the droplet. Secondly, the back-scattered signal from a sufficiently large, trapped, oscillating droplet is shown to be strongly related to its height in the direction of the beam axis. These principles provide ways of monitoring oscillations, decomposing the motion into normal modes, and acquiring the fluid viscosity.

8810-66, Session 14

Laser trapping dynamics of 200 nm-polystyrene particles at a solution surface

Ken-ichi Yuyama, National Chiao Tung Univ. (Taiwan); Teruki Sugiyama, Instrument Technology Research Ctr. (Taiwan); Hiroshi Masuhara, National Chiao Tung Univ. (Taiwan)

Laser trapping due to radiation pressure of a focused laser beam has been widely employed to trap and manipulate nanoparticles in solution. Their researches have been carried out mainly inside the solution, while the importance of laser trapping at a solution surface is recently being recognized for our laser trapping crystallization experiments. In this work, we present a comparison of laser trapping behavior of 200 nm-polystyrene particles in a solution and at a surface layer. The sample solution (2–4x10^11 particles/ml) was prepared by adding D2O into the colloidal solution. When a continuous-wave laser beam of 1064 nm was focused into the inside of the solution film through an objective lens (60x magnification, NA=0.90), the particles were trapped and the resultant assembly was confined in the focal volume. On the other hand, upon focusing the laser at the solution surface, the particles were initially gathered at the focal spot, and then the assembly was extended to the outside and became much larger than the focal volume. Interestingly, the assembly prepared at the surface was observed as colored under halogen lamp illumination with a CCD video camera. The result indicates that the assembly has a periodic structure and can be deemed as a colloidal crystal. This formation process of the colloidal crystal is considered from the viewpoint of radiation pressure acting on nanoparticles at a solution surface. These findings will also lead to deep understanding of the mechanism for laser trapping-induced formation of molecular crystals at a solution surface.

8810-67, Session 14

An optical platform for the production, trapping, manipulation and visualisation of low interfacial tension emulsion droplets

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We discuss the design, implementation and performance of a novel platform for the production and optical control of ultra-low interfacial tension droplets in the 1-10 micron regime. A custom-designed integrated microfluidic system allows the production of oil-in-water emulsion droplets of controllable size and provides an optimised physical platform in which individual droplets are selected, trapped and shaped using a combination of holographic optical tweezers and extended optical landscaping. The structure of the shaped droplet is interrogated by a combination of conventional brightfield imaging and fluorescent structured-illumination sectioning. We detail the problems and limitations of closed-loop holographic control of droplet shape

8810-68, Session 14

Optical control of shape-morphing liquid crystal elastomeric particles

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Robust optical control of shape of birefringent colloidal microparticles is of great fundamental and practical interest but so far has not been demonstrated. In our study, liquid Crystal (LC) elastomeric particles with initial cylindrical shapes and nematic director along the cylinder axis are obtained by means of soft lithography, polymerization in a strong magnetic field, and subsequent infiltration with gold nanospheres [1]. By utilizing nanoparticle-mediated photothermal energy transfer from laser light to heat and inherent coupling between the temperature-dependent ordering and shape, we bend and morph the elastomeric microparticles to obtain long-term-stable well-controlled complex particle shapes [2]. This manipulation is performed in both isotropic and anisotropic LC host fluids [1,2], allowing for a spontaneous elasticity-mediated realignment in the latter case. These findings may impinge on shape-controlled self-assembly of adaptive composite materials and development of light-driven micromachines.

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8810-69, Session 14

Tunable optofluidic microlasers based on optically stretched emulsion droplets

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Dye-doped liquid microdroplets represent active ultrahigh-Q optical cavities that enable observation of dye lasing with threshold pump power significantly lower than that required for bulk samples. An important advantage of liquid micro-cavities over their solid counterparts lies in the possibility of readily adjusting their shape, size, and composition, which opens up the way towards controlled tuning of the emission spectral characteristics of liquid microlasers. However, despite demonstrations of spectral tuning of liquid micro-cavities surrounded by air or solid elastomer, fully reversible tuning of cavities formed by emulsion microdroplets has not been shown yet even though this configuration is of particular practical interest for integrated lab-on-a-chip applications.

Here, we introduce a tunable optofluidic microlaser based on dye-doped emulsion microdroplets confined in a dual-beam optical trap that is formed by two counter-propagating non-interfering Gaussian laser beams. Transparent emulsion microdroplets with refractive index higher than that of the host liquid are confined on the beam axes by the optical gradient force. Trapped droplets are then stretched along the beam axes as a result of the momentum balance of photons transmitted through the droplet / host liquid interface. In order to initiate dye lasing, the droplets are pumped with a pulsed green laser beam. Subsequently, droplet stretching deformation is changed by adjusting the power of the dual-beam trap which leads to the modification of the resonant modal path length and, thus, shift of the microlaser emission wavelength. Using this technique, we demonstrate reversible spectral tuning of the lasing modes.

8810-70, Session 14

UV-induced photopolymerization in the presence of radiation pressure

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Almost applications of the optical trapping have been focused on manipulating small objects. In contrast, we show a new approach to control chemical reactivity by using radiation pressure in the present paper. We have induced photopolymerization (network formation) of an acrylate solution in the optical trapping potential of focused near-infrared (NIR) laser light to investigate the effect of radiation pressure on the solidification of the acrylate solution induced by ultraviolet (UV) exposure. The UV light irradiation to the initiator in the acrylate solution started the polymerization and the chain propagation followed. Although the radiation pressure had no apparent effect on monomers with a low molecular weight, it was able to collect rather long polymer chains under the propagation. In addition, the increase in the local concentration of propagating chains increased the chance of the termination of the polymerization at the focal point of the trapping laser beam. Owing to the collection of the polymer chains and the increase in the chance of chain-termination by the trapping potential, we successfully confined photoproducts in a narrow space, resulting in the solidified structure with the size of ca. 200 nm. Our approach enabled to produce solidification volumes smaller than those achievable with conventional one-photon polymerization, enabling the fabrication of tiny polymeric structures that are smaller than the diffraction limit of the trapping light. This is the first demonstration of a radiation pressure effect on a photopolymerization.

8810-88, Session PWed

Time-averaged force fields for nonspherical particles using position-only measurements

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Optical tweezers can exert and measure forces on the piconewton scale. They can trap and manoeuver microscopic particles. To measure forces, the optical trap needs to be calibrated. As a particle is held in the trap, it still undergoes Brownian motion. Its position distribution relates to the Boltzmann distribution, which allows us to map a potential, and force, to a position in the trap. This method of calibration, often referred to as the `equipartition method', does not assume a quadratic potential or a linear spring model.

Trapping a nonspherical particle would be more appropriate for purposes such as atomic force microscopy with an optically trapped probe. A more ideal shape would be something resembling a pointed cylinder. The difficulty with nonspherical particles is that optical forces depend on the orientation and we can no longer represent to force with a potential. We extend this equipartition method of calibration by trapping a nonspherical particle and calculating its potential averaged over orientation, its `pseudopotential'. This pseudopotential gives the average force field acting on the particle in the trap.

Here we simulate the calibration a trap with a cylindrical particle with the T-matrix method. We calculate the forces acting on an optically trapped cylinder undergoing translational and rotational Brownian motion. There is close agreement between the calculated averaged force and the actual force exerted on the cylinder, even for nonlinear regions of the trap.

8810-89, Session PWed

Towards the absolute measurement of forces on arbitrary shaped particles in optical tweezers

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Recently there has been significant interest in using non-spherical probe particles in optical tweezers. Non-spherical particles experience forces not just as a function of position, but orientation as well. As a result calibration can be problematic due to the added complications. Here we present methodology towards measurement of force in optical tweezers in an absolute sense to minimize the amount of calibration required to characterize forces for different particles. In general this is difficult as the measured values from detectors have responses which are dependent on the particular configuration of the optcial set up used. Characterization of these variables will improve the accuracy of using a single (or small sample) particle-detector calibration. This investigation starts with highly-correlated position/force measurements and uses a particular calibration for one particle on another and determines if the calibration can indeed be made absolute.

8810-90, Session PWed

Back focal plane interferometery detection method in optical tweezers: intensity pattern consists of two anti-correlated areas

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Tightly focused linearly polarized laser beam through high Numerical Aperture (NA) objective lens, which is called ``Optical Tweezers" can trap small objects with a refractive index greater than that of the surrounding medium. Measurement of the trapped particle's position with nanoprecision allows unknown pico-Newton-range forces measurement. The most popular detection method, Back Focal Plane (BFP) interferometry is applicable by the using Quadrant Photodiode (QPD) located at the BFP of the condenser. This method provides 3D detection of the trapped object position with nanometer resolution.In this research we show, both by theory and experiment that the interference intensity pattern due to scattered and unscattered laser beam from trapped particle at the BFP of the condenser consists of two distinguishable areas with anticorrelated intensity changes when the bead is moved in the axial direction. So in order to obtain a reasonable axial sensitivity, one has to eliminate outer area of the aforementioned pattern by decreasing the NA of the condenser. This could significantly increase the axial sensitivity and that the axial calibration is not even possible when the whole intensity pattern is collected by QPD. We also show that the space angle defining the border of two areas linearly depends on the NA of the objective. Moreover we proposed a new Octant Photodiode(OPD), which could significantly improve the axial sensitivity along with maximal lateral sensitivity compared to the commonly used QPD technique.

8810-91, Session PWed

Hydrodynamic synchronisation of optically driven spheres

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Coordinated motion at low Reynolds number is widely observed in biological micro-systems, but the underlying mechanisms are often unclear [1]. We use holographic optical tweezers to experimentally study this phenomenon, by employing optical forces to drive a pair of coplanar microspheres in circular orbits with a constant tangential force. We particularly explore the timescales of their synchronisation from large initial phase differences. We find that this timescale is dependent on how stiffly the microspheres are confined to their circular orbits, and our findings show good agreement with an analytical description of this system [2] and numerical simulations.

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8810-93, Session PWed

Creation of three-dimensional volume chain under high numerical aperture illumination

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In this paper, we propose a method to create three-dimensional volume chain under high numerical aperture illumination. We have investigated a reversal construction of desired focused field through designing an electric-magnetic dipole array and studying its reversal radiation. The dipole factor can be modulated and optimized purposefully. For the selected initial phase difference, amplitude ratio and adjacent space, the radiation of the electric-magnetic dipole array can be seen as a reversal construction of three-dimensional volume chain. The structure of the chain can be modulated freely by changing the dipole factor. We give a procedure to create this chain as an example by using a high numerical aperture (NA=0.95) objective lens obeying the sine condition and discuss its intensity distribution near the focus. This dipolar-shaped focus field will meet potential applications in multiple particles trapping, delivering and self-assembling.

8810-94, Session PWed

Surface-plasmon-based optical trapping of hard nanoparticles: two-dimensional closely packed assembly of polystyrene nanospheres on a metallic nanostructure

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Localized surface plasmons (LSPs) have been investigated for applications such as highly sensitive spectroscopies and the enhancement of photochemical reactions. These applications are enabled by the enhancement effect of an incident resonant electromagnetic field (EMF) at the surfaces of noble metallic nanostructures. In particular, the application of LSP has recently attracted much attention for achieving the effective optical trapping of nanoparticles; this is called LSP-based optical trapping (LSP-OT). LSP-OT possesses several advantages; (i) the EMF enhancement effect of LSP enables the incident light intensity to be significantly reduced for stable LSP-OT, (ii) a nano-sized object can be trapped in a nano-space whose volume is much smaller than that of conventional optical tweezers (diffraction limit), (iii) a large and complicated optical set-up is not necessary, and (iv) this technique can potentially be combined with microfluidic devices. That is, plasmonic substrates can work as “double-functional” devices where biomolecules trapped by LSP-OT can subsequently be analyzed on the basis of SERS or fluorescence enhancement.Thus, LSP-OT could enable a new technique for manipulating not only nanoparticles, but also smaller molecules such as polymer chains, proteins and DNA. Here, we will present the demonstration of LSP-OT of fluorescent-labeled polystyrene nanospheres (PsNs). We discuss multiple optical trapping in which a closely packed 2D hexagonal assembly appeared on a metallic nanostructure.

8810-95, Session PWed

Optimization of the diffraction efficiency of a spatial light modulator through phase error minimization

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Spatial light modulators (SLMs) are commonly used to diffract light beams for a variety of applications. In particular, optical tweezer trapping has greatly benefited from the advent of phase-mostly and phase-only SLMs to write holograms that produce multiple traps. We are using holographic optical tweezers to trap multiple sensor particles in a lab-on-a-chip measurement platform. As part of this program, we have developed a method for optimizing the diffraction efficiency of a SLM. This general method can be applied in situ and addresses the issues of nonlinear phase modulation and phase modulation less than 2π.

The method employs a one-dimensional blazed phase grating. For an ideal SLM, the phase shift is linear and covers 0-2π, yielding a diffraction efficiency of unity. For a realistic SLM with nonlinear or reduced phase shift, the diffraction efficiency is approximately η=1-δ^2, where δ^2 is the variance of the phase difference from the ideal case. Because each pixel contributes to the phase difference independently, this suggests a method to maximize the efficiency by adjusting the phase encoding of the SLM pixel-by-pixel. In practice, we do this by adjusting the gray-scale of each pixel while measuring the first-order diffraction. The collection of optimal gray values comprises the optimized gray-scale lookup table, which exhibits the nonlinearity required to produce a linear phase grating and the saturated phase encoding that maximizes the efficiency of phase limited SLMs. We have successfully applied this optimization method to two different SLMs.

8810-96, Session PWed

Combined single-molecule manipulation and localization for the study of lac Repressor 1D-diffusion along DNA

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Lac repressor (LacI) is a protein representative of a family of DNA binding proteins called transcription factors. These proteins regulate gene expression upon binding to a specific DNA sequence, called target or cognate. LacI cognate site is called operator. The association rate to the target is limited by the time required to search the short operator sequence within the whole genome. A theoretical calculation, based on random collision during 3D-diffusion, gives a rate of 108M-1s-1. Nevertheless, the first measurements of association rate produced a value of 1010M-1s-1, two orders of magnitude faster than the theoretical value. The most accredited model to explain this discrepancy is the ‘facilitated diffusion’ model, according to which the protein, before encountering the target sequence, alternates between 3D-diffusion and random association to non-cognate DNA; during such non-specific interactions the protein undergoes a 1D-diffusion along DNA.

Here we analyzed diffusion properties of LacI under varying force applied to a single DNA molecule. This was made possible by an experimental set-up combining single molecule nanometric localization and optical trapping to track a single fluorescently labeled LacI molecule bound to a DNA molecule suspended in solution, far from the cover slip. The double optical tweezers employed allow application of controlled tension on DNA. To localize the protein, we used a rapid and accurate algorithm based on the calculation of the radial symmetry center. We obtained the 1D diffusion coefficient and sliding length under different DNA tensions.

8810-97, Session PWed

Resonant optical trapping utilizing nonlinear optical effects

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During recent years, the size of targets of optical manipulation is shifting to nanometer scale. For this matter, our group has previously proposed the optical manipulation by using electronically resonant optical response of nanostructures to enhance a radiation force and to select particular kinds of nanoparticles via quantum confinement effect [1]. Further, recently, we have proposed nonlinear resonant laser manipulation, which coherently elucidates recent reported puzzling phenomena contradicting with the conventional understanding of the resonant optical trapping [2]. In addition, we have demonstrated some unconventional forms of the optical manipulation utilizing nonlinear optical effects [2].

In this contribution, on the basis of our theory, first, we describe a method to trap single organic molecules utilizing nonlinear effects that is more effective than ever before. Then, we show it possible to sort single organic molecules by their energy levels using a pulling force. The results demonstrate that the resonant optical trapping utilizing the nonlinear optical effects has advantages in trapping single organic molecules and enhancing the degree of freedom to manipulate nano-objects.

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8810-98, Session PWed

Ray optics in combination with the Gaussian beam propagation method for optical trapping of free-shaped particles in microfluidic systems

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In this paper we present a novel model for optical trapping, in which different assets are combined to realize a flexible model for the calculation of optical forces and torques on free-shaped particles relevant to cell applications. The actual optical force and torque estimation, based on a ray optics approach, of the optical trap can easily be integrated in the scheme simulating the surrounding microfluidic chip with integrated micro-optics. The propagation of the trapping laser light exiting the optical fibers and going through this micro-optical chip is ensured by the Gaussian Beam Propagation Method. It allows a realistic propagation of Gaussian beams in and near the Rayleigh range. Various beam profiles can be implemented using this method. Back-reflected rays into and outside the particle are considered by using a non-sequential ray-tracing model. We present the flexibility of our model from different points of view and validate it. Our model enables the prediction of circumstances in which cells are trapped and how they behave in the optical trap. Consequences of alignment errors in the optical trap device can be efficiently simulated. Therefore, our model would suit for designing an integrated dual fiber optical trap into a microfluidic chip. The ultimate goal of this model is to introduce it for micro-optical systems for biomedical applications, in particular the identification of single cells.

8810-99, Session PWed

Numerical simulation of Brownian particles in optical force fields

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Some randomness is present in most phenomena, ranging from biomolecules and nanodevices to financial markets and human organizations. However, it is not easy to gain an intuitive understanding of such stochastic phenomena, because their modeling requires advanced mathematical tools, such as sigma algebras, the Itô formula and martingales. Here, we discuss a simple finite difference algorithm that can be used to gain understanding of such complex physical phenomena. In particular, we simulate the motion of an optically trapped particle that is typically used as a model system in statistical physics and has a wide range of applications in physics and biophysics, for example, to measure nanoscopic forces and torques. First, we will explain how to simulate a random walk and how to treat the white noise term within a finite difference framework. We will then describe how to simulate the free diffusion of a Brownian particle and study its transition from the ballistic to the diffusive regime due to the presence of inertial effects at short time scales, and examine the effect of an optical trap on the motion of the particle. We also outline how to use simulations of optically trapped Brownian particles to gain understanding of nanoscale force and torque measurements, and of more complex phenomena, such as Kramers transitions, stochastic resonant damping, and stochastic resonance.

8810-100, Session PWed

Intracavity optical trapping with feedback locked diode lasers

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The first optical tweezers (OT) was realized using a laser beam strongly focused by a high numerical aperture objective lens. In these systems, a particle is trapped in the focal region by the radiation forces arising from the particle's light scattering. Since then, OT have been extensively used for applications in cellular and molecular biology, soft matter, nanotechnology and physics. The ability to apply forces in the range of femto- to picoNewton on nanoparticles and to measure their displacements with nanometer precision is crucial for the investigation of colloidal and condensed matter systems. More recently OT have been also used to manipulate, rotate and assemble a variety of nanostructures, such as carbon nanotubes, nanowires, polymer nanofibers, graphene flakes dispersed in water and metal nanoparticles and aggregates. Here we demonstrate a novel approach to optical trapping based on optical feedback-locking that can be applied with low numerical aperture lenses (NA= 0.35, 0.45). In this novel configuration the optical feedback on the diode laser source is controlled by the light scattering from a trapped particle. When no particle is in the trap, the optical feedback from a dielectric mirror (external mirror) posed above the microscope objective will increase the trapping power in the focal spot. Instead, when a particle falls in the trap, the trap will work at low power preventing damage and relaxing the stringent conditions on high numerical aperture for standard OT. In this novel configuration we can achieve stable optical trapping at very low power (0.3 mW) with injected current close to the threshold current of the diode laser, with a large field of view and a long working distance. This technique is very useful for dealing with biological samples which need very low power to prevent photodamage.

8810-101, Session PWed

Rayleigh scattering correlation spectroscopy on diffusion dynamics of nanoparticles under intense laser irradiation

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White light continuum generated by focusing femtosecond laser pulses (100 fs, 800 nm, 80 MHz) to a photonic crystal fiber is an excellent probe light for Rayleigh scattering spectroscopy. By using white light we have developed light scattering spectroscopy and imaging system for studying nano-materials, single living and plant cells, and so on. Here we report Rayleigh scattering correlation spectroscopy on diffusion dynamics of various nanoparticles in solution under intense laser irradiation. Diffusion time was estimated by conventional analysis under various conditions. In case of gold nanoparticles with a diameter of 100 nm, the diffusion time measured with 35 uW probe light intensity is constant at observation wavelength range of 500-700 nm. This indicates that no additional effect is involved upon irradiation of surface plasmon resonance (SPR) band. On the other hand, however, the diffusion time measured with higher probe intensity gives interesting wavelength dependences. At 532 nm the diffusion time decreases to one-fourth when the intensity was increased from 1 to 100 mW, while no clear dependence was obtained at 800 nm. As SPR band of this nanoparticle is located around 580 nm, we consider that the probe light absorbed by the gold nanoparticle results in photothermal heating, leading to vigorous diffusion. Such heating effect is not appreciable at 800 nm, but gradient force may be exerted at 100 mW. We are examining such complex diffusion dynamics of various nanoparticles under intense laser irradiation and will report how SPR will affect diffusion through heating and trapping.

8810-102, Session PWed

Rotation of optically trapped plasmonic nanoparticles by circularly polarized light

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The fact that light carries spin and orbital angular momentum can be utilized in rotating nanoparticles simply by targeting them with a beam of light. The spin angular momentum is transferred to a particle by absorption which induces a torque to the absorbing particle. The torque is counteracted by the drag force in the case of viscous medium resulting in constant rotation frequency of the particle about its own axis.

Sub-wavelength sized particles have optical properties that are significally different from their macroscopic counterparts. Noble metal nanoparticles are particularly interesting in this respect because they support surface plasmon resonances that have profound influence on the optical force interactions. Plasmonic particles have also high absorption close to their resonance which makes them interesting candidates for the rotation experiments.

In this work, we have used a single Gaussian beam laser tweezers constructed around an inverted optical microscope to trap particles two-dimensionally and investigate the interaction between circularly polarized light and plasmonic nanoparticles. The particles are illuminated with dark field condenser and the scattered light is detected with avalanche photo diode and analyzed by an autocorrelator. The rotation frequency is analyzed from the autocorrelation signal of the scattered intensity.

The particles used in the measurements consist of plasmonic nanowires, nanorods and nanobeads made of silver and gold. As we demonstrate, the nanowires reach rotation rate of few turns per second whereas for the nanobeads the rotation frequency is considerably higher. Fast rotation of nanopartices could be beneficial in biophysics, microfluidics and in sensing technology.

8810-103, Session PWed

Optical trapping of anisotropic nanocylinder

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For modeling optical trapping of an anisotropic nano-particle we first used the point matching method to compute the T-matrix coefficients based on the boundary condition for the normal componants of D-fields. In the anisotropic media, where the divergence of E-field is non-zero, the Maxwell wave equations was sloved in the Fourier space. Thus, the plan waves with angular spectrum amplitude distributions can be expanded into the orthogonal and complete set of the Vector Spherical Wave Functions. The E-field eigenvectors can be obtained by the characteristic equation. In the point-matching mthod however we do not need to solve the entire internal field in the anisotropic particle, but an expression of the unknown internal field at the boundaries. We computed the stress distribution on the interfaces of an anisotropic nanocylinder and the related total lateral torque, spin torque and total force in the optical tweezers in order to put in evidence for mecanism of the optical trap of the anisotropic particle. The trapping beam was modeled as the vector Gaussian beam with high order corrections. After solving the scattered field the radiation stress was computed through the Maxwell stress tensor for anisotropic media by Robinson. Our calculation showed that optical stress can be not normal to the interface of anisotropic media. Our calculation predicted that when the optical axes of the anisotropic nanocylinder are not aligned with the cylinder axis, the nanocylinder can be trapped inclined with respect to the beam axis at an equilibrium position. Preliminary experimental observations came to support this prediction.

8810-104, Session PWed

Sorting bacteria of different shape by specially designed optical traps

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We demonstrate optical trapping and sorting of Bacillus thuringiensis and Micrococcus luteus bacteria. We can select from between two types of Gram-positive bacteria by using novel beams which trap only one of two separate morphologies. In our research we looked at rod and spherical shaped bacteria to develop a sorting method, which can be later applied for more dangerous bacterium such as Bacillus anthracis, which is the etiologic agent of anthrax. We use a holographic optical tweezer system with custom designed beam profiles created to optimally fit and optically manipulate predominately only one type of bacteria and not another. This technique allows us to specificity trap only one strain of bacterium in order to look at the cytokinesis of each type of bacteria independently and separate pairs of bacteria from each other.

8810-105, Session PWed

Analysis of sperm energetics and motility in viscous solutions using optical tweezers

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We have previously reported that increasing viscosity physically affects the mechanical properties of human sperm motility. When sperm encounter a viscous environment their swimming force increases with increasing viscosity while their curvilinear velocity (VCL) decreases with increasing viscosity. Additionally, sperm probed with the mitochondrial membrane potential dye DiOC6 showed no increase in aerobic respiration while under these conditions.

The aim of the present was to characterize sperm energetics while closely monitoring the sperm's swimming force and VCL, and at the same time inhibit aerobic and anaerobic metabolic pathways. Multiple sperm were optically trapped using a 1064 nm Nd:YVO4 continuous wave laser and tracked in increasing viscous solutions while inhibiting the sperm's anaerobic pathway using 2-deoxy-d-glucose (DOG). Additionally experiments were done using carbonyl cyanide m-chlorophenyl hydrazone (CCCP) to inhibit the aerobic pathway. Analysis of the data showed that inhibiting either pathway caused a decrease in swimming force and VCL when compared no inhibition-controls. The trend of swimming force increasing with increasing viscosity was still observed when inhibiting either energetic pathway. When both inhibitors were used simultaneously, the sperm motility was either reduced to zero or dramatically decreased. These results support our hypothesis that viscosity affects the sperm physically rather than through the metabolic pathways associated with ATP production.

8810-106, Session PWed

Monolithic PMMA stretcher chip with integrated DUV induced waveguides

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The design and implementation of a monolithic microfluidic optical stretcher and manipulation chip is presented. The microfluidic chip is fabricated in a low cost polymer, poly(methyl metacrylate) (PMMA), by hot embossing, and integrated waveguides are defined by deep UV (DUV) exposure of the PMMA. The DUV absorption alters the refractive index of the PMMA locally and enables monolithical integration of single mode optical waveguides into the microfluidic chip. The DUV induced waveguides exhibit propagation losses in the range of dB/mm, comparable to other integrated polymer waveguides. The fabrication procedure, characterization of the optical waveguides, and initial trapping and manipulation experiments are presented. A Matlab script was developed for tracking manipulated particles and used to characterise the optical forces in manipulation and trapping experiments.

The device layout is compact and is easily extendable to multiple-waveguide trap configurations integrated with microfluidic sample preparation. Moreover, the fabrication is upscalable, pointing to cheap, single-use chips.

8810-107, Session PWed

Manipulation of yeast cells with DOE-modulated crescent-shaped and optical bottle laser beams

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This work is dedicated to the study of micromanipulation techniques using DOE-modulated laser beams. Two kinds of crescent-shaped and optical bottle beam kinds are covered. The numerical model for the calculation of light damage and optical forces exerting by the modulated beams on a trapped particle is provided. The study also contains experimental results on the trapping and manipulating of yeast cells with modulated laser beams. They show that modulated beams are in some cases are more efficient than widely used Gaussian beam: crescent beams are able to achieve better trap stiffness than Gaussian at the price of altered spatial distribution of that stiffness. Optical bottles are beneficial for their ability to hold the trapped object by its edges therefore decreasing amount of light energy absorbed by the microbiological samples.

One of the significant features of the work is that the DOE for the beam modulating is not a dynamic modulator but actually etched on the glass relief. This technique gives better energoefficiency and higher quality of the beam profile.

The theoretical part of the work consists of the numerical modulation of the capturing process using RO-regime and ray-tracing algorithms to compute light propagation through the cell model. The model takes into account inner cell structure and ray-tracing is also used to project optical damage.

The experimental part consists of series of actual trapping and manipulating with Saccharomyces cerevisiae cells. For all the beam types trap stiffness is measured.

Crescent beams give 2-4 times better trap stiffness than Gaussian beams.

8810-108, Session PWed

Direct measurement of formation of loops in DNA by a human tumor suppressor protein

Amy Migliori, Douglas E. Smith, Samuel C. Kung, Univ. of California, San Diego (United States); Danielle Wang, Univ. of California, Irvine (United States)

In previous work we developed methods using optical tweezers to measure protein-mediated formation of loops in DNA, structures that can play an important role in regulating gene expression. We previously applied this method to study unusual restriction endonucleases, which were convenient model systems for studying this phenomenon. Here we report preliminary work in which we have applied this method to study p53, a human tumor suppressor protein, and show that we can measure formation of loops. Previous biophysical evidence for loops comes from relatively limited qualitative studies of fixed complexes by electron microscopy. Our results provide independent corroboration and future opportunities for more quantitative studies investigating structure and mechanics.

8810-109, Session PWed

Longterm effects of inertia on a Browian particle studied by optical tweezers

Giuseppe Pesce, Univ. degli Studi di Napoli Federico II (Italy); Giorgio Volpe, Institut Langevin (France); Antonio Sasso, Univ. degli Studi di Napoli Federico II (Italy); Giovanni S. Volpe, Bilkent Univ. (Turkey)

The effects of the inertia on a Brownian particle diffusing in a fluid are usually considered negligible. Only at very small times, i.e. times of the order of magnitude of the ratio m/gamma, deviations from the Einstein-Smoluchowsky law have been recently reported taking into accounts also the effects of the fluid displacement. Using blinking optical tweezers and fast video microscopy we show that these effects are measurable even at long times, up to few tenths of seconds. In particular the deviation from the Einstein-Smoluchowsky law increases with the time.

8810-110, Session PWed

Testing a structural model for viral DNA packaging motor function by optical tweezers measurements, site directed mutagenesis, and molecular dynamics calculations

Nicholas A. Keller, Douglas E. Smith, Gaurav Arya, Univ. of California, San Diego (United States); Venigalla Rao, The Catholic Univ. of America (United States); Amy Migliori, Univ. of California, San Diego (United States)

Many double-stranded DNA viruses employ a molecular motor to package DNA into preformed capsid shells. Based on structures of phage T4 motor proteins determined by X-ray crystallography and cryo-electron microscopy, Rao, Rossmann and coworkers recently proposed a structural model for motor function. Specifically, they proposed that DNA is ratcheted by a large conformational change driven by electrostatic interactions between charged amino acids at an interface between two globular domains. We are currently working on testing this model by studying the effect of site-directed changes altering the charges of these amino acids on packaging dynamics measured in detail with optical tweezers. We are also use molecular dynamics simulations to predict alterations in free-energies caused by these changes. We report preliminary work in which several amino acid changes are predicted to have significant effects and are indeed clearly observed to alter the measured motor dynamics.

8810-111, Session PWed

Evidence for non-equilibrium dynamics in viral DNA packaging from optical tweezers measurements

Zachary Berndsen, Nicholas A. Keller, Douglas E. Smith, Univ. of California, San Diego (United States)

Tight confinement of double-stranded DNA molecules in viruses is an energetically unfavorable process driven by a powerful molecular motor complex. Here we present preliminary results that suggest a significant influence on these forces of non-equilibrium dynamics of the confined DNA. In one approach we measure changes in the packaging dynamics of single complexes following stalling and restarting of the motor. In a second complementary approach, we analyze heterogeneity in packaging dynamics within a large ensemble of individual complexes. Both measurements suggest the formation non-equilibrium DNA conformations with very long relaxation times compared with free DNA.

8810-112, Session PWed

Analysis of single-molecule mechanical measurements with high spatio-temporal resolution

Marco Capitanio, Lucia Gardini, European Lab. for Non-linear Spectroscopy (Italy); Francesco S. Pavone, Univ. degli Studi di Firenze (Italy)

Optical tweezers allow recording mechanical data from single biological molecules such as molecular motors, DNA processing enzymes, nucleic acids. Such data consist of time series that are dominated by thermal noise and such noisy recordings require proper analysis to correctly extract kinetic and mechanical information. Several different analysis approaches have been established in the past years. Here, we propose an analysis method for optical trapping recordings of non-processive motor proteins. The method does not assume any particular interaction kinetics, allows detection of sub-millisecond interactions and quantification of the number of false and lost events. Precise alignment of interaction events and ensemble averaging allow the investigation of the stepping dynamics of non-processive motors with a temporal resolution of few tens of microseconds and a spatial resolution of few angstroms. Our analysis is applied to the study of the motor protein myosin from fast skeletal muscle. Thanks to the high spatio-temporal resolution, we can distinguish three mechanical pathways in the acto-myosin interaction, with several orders of magnitude different kinetics, which contribute in a load-dependent manner to the myosin working stroke.

8810-71, Session 15

Optical manipulation using speckle fields

Giorgio Volpe, Institut Langevin (France); Giovanni S. Volpe, Bilkent Univ. (Turkey); Sylvain Gigan, Institut Langevin (France)

Current optical trapping techniques rely on carefully engineered optical systems; since the quality of the trapping is strongly dependent on the quality of the focus, these systems have to be very carefully aligned and optimized. It is therefore still a challenge to manipulate a large number of particles when the environment is not well controlled and known a priori such as in most biological, biomedical and microfluidic applications. Here, we developed a novel technique for optical manipulation based on speckle light fields. These fields arise naturally when coherent light impinges on scattering systems (biological tissues, turbid liquid, non-transparent microfluidic devices or rough surfaces) and, while the produced speckle pattern is random, it has well-defined statistical properties, such as its distribution of intensity and correlation length. We experimentally show how to take advantage of such properties in order to perform optical manipulation tasks such as trapping, guiding and sorting. In particular, we demonstrated the sorting of Brownian particles of different size and refractive index in a microfluidic device. To perform such tasks, an incident laser power as little as a tenth of milliwatt per square micrometer is needed, and, apart from the excitation laser, all the components needed to generate the speckle pattern can be integrated in the walls of the microfluidic chamber. The simplicity of this technique will foster its application in biological and biomedical applications where automated and turn-key techniques are especially appreciated.

8810-72, Session 15

Adaptive optics and aberration correction in optical tweezers

Amanda J. Wright, The Univ. of Nottingham (United Kingdom); Caroline Müllenbroich, Niall McAlinden, Univ. of Strathclyde (United Kingdom)

Optical aberrations are a well-known problem in optical tweezers, particularly when users wish to take quantitative measurements at depth into samples. Without any aberration correction the strength and quality of the trap can be seen to clearly deteriorate with trap depth. Here we use a technique called Adaptive Optics, common in optical astronomy, to correct for the optical aberrations in an optical tweezers system. Adaptive Optics works on the principle of shaping the incoming wavefront with the equal but opposite distortion to that caused by the optical system and the sample so as to restore image quality, or in this case trap strength. The Adaptive Optics system used here is a sensor-less system, with a deformable membrane mirror as the correction element and a random search optimisation algorithm that determines the aberration correction required. Crucial to the success of this technique is the choice of merit factor the algorithm uses as a measure of improvement. The novel merit factor employed here is determined by measuring the displacement of a bead from its equilibrium position when exposed to a viscous drag force. The benefit of this merit factor is that it is inversely proportional to the stiffness of the optical trap, the property we aim to improve. We demonstrate the success of this technique by increasing our maximum trapping depth from 136 µm to 166 µm and increasing the trap strength by a factor of 4.37 and 3.31 for the x- and y- axis respectively at a depth of 131 µm.

8810-73, Session 15

Spatial light modulation for improved microscope stereo vision and 3D tracking

Michael P. Lee, Boulder Nonlinear Systems (United Kingdom) and Univ. of Glasgow (United Kingdom); Graham M. Gibson, Univ. of Glasgow (United Kingdom); David B. Phillips, Univ. of Bristol (United Kingdom); Stefan Bernet, Monika Ritsh-Marte, Innsbruck Medical Univ. (Austria); Miles J. Padgett, Univ. of Glasgow (United Kingdom)

We present a new type of stereo microscopy which can be used for tracking in 3D over an extended depth. The use of Spatial Light Modulators (SLMs) in the Fourier plane of a microscope sample is a common technique in Holographic Optical Tweezers (HOT). This set up is readily transferable from a tweezer system to an imaging system, whereby the tweezing laser is replaced with a camera. Just as a HOT system can diffract many traps of different types, in the imaging system many different imaging types can be diffracted with the SLM. The type of imaging we have developed is stereo imaging combined with lens correction. This approach has similarities with human vision where each eye has a lens, and it also extends the depth into the sample that we are capable of accurately tracking particles.

8810-74, Session 16

Optical binding induced assembly of Ag nanoparticles in shaped light fields

Zijie Yan, Raman Shah, Uttam Manna, The Univ. of Chicago (United States); Gray Stephen, Matthew A. Pelton, Argonne National Lab. (United States); Norbert F. Scherer, The Univ. of Chicago (United States)

Optical binding interactions can lead to spatial arrangements of particles in light fields via the potential gradients created by the interference of incident and scattered light,1 and the phenomenon has been widely studied for micron and sub-micron size particles.2, 3 Here we show optical binding of multiple Ag nanoparticles with diameters of 40 nm in solution using shaped light fields with a wavelength of 800 nm, and extend the demonstration of optical binding into the Rayleigh regime where the particles can be well approximated as point dipoles.4 Specifically, ordered clusters were formed in cylindrically symmetric optical traps, and linear chains were formed in line traps. We extended the coupled-dipole model to describe optical binding of multiple particles, and the model successfully predicted many experimental results. Moreover, for Ag nanoparticles with diameters of ~100 nm, the strong optical binding forces can assemble the particles into regular arrays, and for Ag nanoparticles with diameters of ~150 nm, optical binding can lead to stable lattices of Ag nanoparticles. These stable lattices, in turn, can serve as templates to trap other smaller objects, e.g., semiconductor quantum dots, in the regions of large field gradients created by multiple scattering and interference. These results demonstrate the possibility to fabricate new hybrid assemblies with strong nonlinear-optical and quantum-optical properties by all-optical methods.

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8810-75, Session 16

Pair interaction and optical binding in 3D random electromagnetic fields

Sergey V. Sukhov, Kyle M. Douglass, Aristide C. Dogariu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

One of the well-known consequences of particle-particle interaction in an external electromagnetic field is optical binding (OB). OB has traditionally been observed between scattering particles located in a controlled, beam-like geometry. As a result of the interaction, they experience attractive or repulsive forces depending on their mutual position. Notably, there are stable positions where the binding force acting on the particles is zero. OB has been comprehensively studied for single wave and counter-propagating wave excitation geometries.

The question whether the interaction between particles and optical binding still exists in incoherent fields is not trivial. It's not clear how the particle-particle interaction is affected by partially coherent illumination or by fields whose correlation length is anisotropic. Furthermore, since the OB force disappears in a temporally incoherent field, one might think that it does so in a spatially incoherent field as well. We have found, however, that this interaction does survive in a fully spatially incoherent field and, moreover, it is a long-range interaction. The finite coherence length of the external field introduces certain peculiarities that will be discussed in the talk, such as the dependence of the magnitude and the periodicity of the interaction potential on the coherent properties of light. The application of the calculated interaction potential for the study of particle dynamics in a cavity will be also discussed.

The non-vanishing force between particles in random, three-dimensional fields has important implications for many field-coupled systems, such as optically-active matter and protein-membrane dynamics in cells.

8810-76, Session 16

Near-field manipulation of interparticle forces through resonant absorption, optical binding, and dispersion forces

David S. Bradshaw, David L. Andrews, Univ. of East Anglia Norwich (United Kingdom)

The relative motions of two or more neutral particles, subject to optical trapping forces within a beam, are influenced by intrinsic inter-particle forces. The fundamental character of such forces is well-known and usually derives from dispersion interactions. However, the throughput of moderately intense (off-resonant) laser light can significantly modify the form and magnitude of these intrinsic forces. This optical binding effect is distinct from the optomechanical interactions involved in optical tweezers, and corresponds to a stimulated (pairwise) forward-scattering mechanism. In recent years, attention has begun to focus on optical binding effects at sub-micron and molecular dimensions. At this nanoscale, further manipulation of the interparticle forces is conceivable on the promotion of optically bound molecules to an electronic excited state. It is determined that such excitation may influence the intrinsic dispersion interaction without continued throughput of the laser beam, i.e. independent of any optical binding. Nevertheless, the forward-scattering mechanism is also affected by the initial excitation, so that both the optical binding and dispersion forces can be manipulated on input of the electromagnetic radiation. In addition, the rate of initial excitation of either molecule (or any energy transfer between them) may be influenced by an off-resonant input beam which, thus, acts as an additional factor in the modification of the interparticle force. A possible experimental set-up is proposed to enable the measurement of such changes in the interparticle force, based on adapted AFM instrumentation.

8810-77, Session 16

Optical binding of non-spherical colloids

Stephen H. Simpson, Univ. of Bristol (United Kingdom); Philip H. Jones, Univ. College London (United Kingdom); Onofrio M. Maragó, Istituto per i Processi Chimico-Fisici (Italy); Simon Hanna, Univ. of Bristol (United Kingdom)

Optical binding effects provide a means of steering the self organization of colloidal particles. Almost all existing studies make use of colloidal spheres. Despite the relative simplicity of this system, a plethora of intriguing observations have been made. For example bistability and hysteresis [1] have been observed in pairs of optically coupled beads, whilst lattice and pattern formation can be achieved for arrays of spheres [2,3]. More recently, extremely strong binding has been observed for spherical metallic nano-particles [4]. Spoiling the spherical symmetry of the particles under consideration adds an additional layer of complexity. Previously, binding forces have been computed between pairs of carbon nano-tubes, using quantum electrodynamics [5]. Here, we classically examine the forces and torques between pairs of low symmetry particles in counter-propagating plane waves. Equilibrium configurations are located and their stability examined. The theoretical results are compared with existing experimental work, and the potential for self organization of novel structures is discussed.

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8810-78, Session 16

Optical sorting due to optical binding

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When several particles are illuminated by intense laser fields there exist also additional optical forces between the particles induced by scattered fields.

This effect is called optical binding and the particles due to their mutual forces induced by light may create optically bound structure.

As these forces are of second order (in comparison to forces induced by the incident fields) they are very sensitive to size or shape of the particles.

We have previously experimentally studied the optical binding in the configurations employing two counter-propagation Bessel beams.

These results were sufficiently supported by our numerical simulations (Coupled dipole method CDM).

We study how the difference of sizes of two spherical particles influences their spatial stable separation.

Even small changes in the limits of particle-size distribution of used particles may lead to experimentally verifiable differences.

The intensities of the two beams must be also tuned to achieve sufficient stability of the whole couple in the experimental sample.

By variation of mutual intensities we may also move the couple along the common optical axis.

Another results may serve for detection of particles of different composition or shape.

Very exciting configuration of "Optical tractor beam" offers another and simple means of optical sorting.

Our numerical results indicate that the behaviour is very sensitive to particles size.

Here we present numerical studies how the sizes of individual particles (within the range of the particle-size distribution) influences the particles dynamics in various optical trapping configurations.

8810-79, Session 17

Micro-assembling with optical tweezers: provisioning solutions for micro manufactured 2PP building blocks

Sarah Isabelle Ksouri, Andreas Aumann, Reza Ghadiri, Sebastian Baer, Andreas Ostendorf, Ruhr-Univ. Bochum (Germany)

Holographic optical tweezers manipulate structures in micrometer range with highest flexibility and precision. As is well known non-spherical assemblies can be trapped and controlled by laser light and assembled with an additional light modulator application, where the incident laser beam is rearranged into flexible light patterns in order to generate multiple spots. The complementary polymer assemblies are generated by a two-photon-polymerization (2PP) process and are not equipped with spherical trapping points. The possibilities of manufacturing arbitrary building blocks and the potential of HOTs lead to the idea of combining manufacturing techniques with manipulation processes. In this work we present how generated structures can be disassembled for replacing defective building blocks for example as well as a sorting solution for 2PP assemblies is introduced. A purpose-built sample holder is developed for a manual intake of 2PP building blocks. The long-term objective is to automate the feeding and provisioning of several different 2PP micro assemblies to realize an automated assembling station.

8810-80, Session 17

Fashioning microscopic tools: the development of a passive force clamp using particle shaping

David B. Phillips, Univ. of Bristol (United Kingdom); Miles J. Padgett, Univ. of Glasgow (United Kingdom); John G. Rarity, Simon Hanna, Mervyn J. Miles, Stephen H. Simpson, Univ. of Bristol (United Kingdom)

By moulding optical fields, holographic optical tweezers are able to generate structured force fields with magnitudes and length scales of great utility for experiments in soft matter and biological physics. Optically induced force fields are determined not only by the incident optical field, but by the shape and composition of the particles involved. Indeed, there are desirable but simple attributes of a force field, such as rotational control, that cannot be introduced by sculpting optical fields alone. We show how force-extension relations for particles in Gaussian traps can be deliberately engineered by fashioning colloids of particular geometries. To demonstrate this, we describe the design, fabrication and application of a passive force clamp, capable of applying a constant force over several microns. The non-linear force-extension characteristics of our sensor can be characterised by rapidly switching the optical trap positions and observing the velocity of the sensor's return to equilibrium. We demonstrate how such a device can be used to image surfaces while exerting a constant force, without the need for feedback control.

8810-81, Session 17

Heat in optical tweezers *(Invited Paper)*

Daniel Jaque Garcia, Blanca del Rosal, Patricia Haro, Laura Martinez Maestro, Univ. Autónoma de Madrid (Spain); William T. Ramsay, Heriot-Watt Univ. (United Kingdom); Emma Martin Rodriguez, Concordia Univ. (Canada); Lynn Paterson, Ajoy K. Kar, Heriot-Watt Univ. (United Kingdom); José García Solé, Univ. Autónoma de Madrid (Spain)

The presence of laser-induced thermal loading in optical traps and tweezers is a well known phenomenon that should be known in detail in order to minimize its effects on trapped objects such as living cells. In this work Quantum Dot based nano-thermometry has been used to determine the magnitude of such heating during single cell trapping. It has been possible to find evidence of the existence of an optimum wavelength that minimizes cell damage. we will show how this optimum trapping wavelength results from the simultaneous minimization of both photo-thermal and photo-chemistry damage. We also present first results on the optical manipulation of plasmonic-based micro heaters and of rare earth doped nano-thermometers (nano-particles) for controlled in vivo photo-thermal treatments. Optically controllable micro-heaters consists on hybrid dielectric particles conjugated with metallic nano-particles capable of efficient heating when excited at the plasmon resonance wavelength. The nano-thermometers are dielectric nano-particles doped with rare earth ions whose luminescence is strongly dependent on environmental temperature.

8810-82, Session 17

Optical tweezers for precise control of micro-bubbles arrays

Tristan Burns, Daryl C. Preece, Timo A. Niemenen, Haliina Rubinsztein-Dunlop, The Univ. of Queensland (Australia)

We use highly focused laser beam to create micro-bubbles. The size of the bubbles is highly controllable and a full optical control is attained. Multiple bubbles can also be created and their size changed independently. The dynamics of such multi-bubble systems are studied. Such bubble systems generate strong flows such as marangoni convection and also large thermal gradients.

However, this can be exploited for the purposes of measurement.

Since the size of such micro-bubbles is highly dependent on the supplied temperature, we anticipate that such systems can be used for precise temperature control of samples. These methods can become of potentially great use when the exact and local temperature profiles are of importance. Furthermore, since bubble expansion can generate orders of magnitude more force than conventional optical forces. Such systems have application in manipulation of particles that cannot be moved by other means. We present methods based on optical tweezers for using the generated bubbles as thermal sensors and as opto-mechanical transducers.

8810-83, Session 17

Femtosecond optical trapping of dielectric nanospheres: three-dimensional mapping of their directional ejections

Wei-Yi Chiang, Anwar Usman, Hiroshi Masuhara, National Chiao Tung Univ. (Taiwan)

By replacing conventional continuous wave- to femtosecond pulsed-laser beam in optical trapping experiment of 50-nm-sized polystyrene beads, we found that the nanoparticles are ejected from the trapping site in directions perpendicular to the laser polarization.1 This phenomenon has been elucidated in detail by using theoretical modelling and numerical approaches of the optical forces based on interaction between single nanoparticles with electromagnetic field of a single pulse, by which we have shown that attractive force components spatially resolved in directions orthogonal to laser polarization are completely overcome by respective repulsive forces.2 These forces may also be important for manipulating or controlling the dynamics of nanoparticles. Assessment of the repulsive forces can be quantitative when migrations of nanoparticles can be visualized in three-dimensions. Since our experimental system uses a single objective lens for both laser trapping and light scattering imaging to observe only the dynamics of nanoparticles at the trapping plane, three-dimensional migrations of the nanoparticles were evaluated by shifting the focal plane along the vertical direction, above and below the trapping site, immediately after the trapping beam was turned off. By doing so, we indeed observed the directional migrations of nanoparticles out of the trapping site in three dimensions. The results suggest that trajectories of the ejected nanoparticles take the shape of a cone with its vertex at the focal center and its axis of symmetry on the plane perpendicular to the laser polarization. This finding leads to a new perspective of optical trapping of nanoparticles by ultrashort laser pulses.

8810-84, Session 17

Measuring colloidal osmotic compressibility of nanoparticle suspension by optical trapping

Jinxin Fu, Vural Kara, H. Daniel Ou-Yang, Lehigh Univ. (United States)

Particle interactions determine the stability of nanoparticle suspensions and the phase separation of particle-polymer mixtures. However, due to the small sizes of the dispersed nanoparticles, it is not easy to directly measure interaction forces between particles in a colloidal suspension. In this paper, we propose an “Optical Bottle” approach to quantify these particle interactions in a suspension by measuring the colloidal osmotic compressibility of the nanoparticles. Virial expansion of the colloidal osmotic compressibility yields virial coefficients of different orders. The second order virial coefficient of aqueous suspensions of colloidal polystyrene nanospheres in the presence of high-salt (KCl) and polyethylene glycol (PEG) is found to decrease with increasing PEG concentration, suggesting an attractive depletion interaction between the PEG-crowed polystyrene particles.

8810-85, Session 17

Optical trapping of high refractive index semiconductor nanocrystals: nanoscale force probes without the heating

Ana Andres Arroyo, Fan Wang, Wen Jun Toe, Peter J. Reece, The Univ. of New South Wales (Australia)

Recent research into developing nanoscale optical trapping force probes has primarily focused on the use of noble metals nanoparticles, such as gold and silver, as they have considerably greater polarizability then standard dielectric spheres of equivalent dimension. The fundamental limitation of this approach is that unavoidable heating is linked with dissipation induced surface plasmons. This heating can be severe at the optical powers required for trapping and can cause non-physiological cell responses. We explore theoretically and experimentally the possibility of using high refractive index semiconductor nanoparticles as a possible alternative to achieving high polarizability whilst operating at a trapping wavelength that is below the band-gap energy where the particles have negligible absorption.

8810-86, Session 17

Optical trapping for tissue scaffold fabrication

Anna M. Linnenberger, Boulder Nonlinear Systems (United States)

We investigate holographic optical trapping combined with step-and-repeat maskless projection stereolithography for fine control of 3D position of living cells within a 3D microstructured hydrogel. C2C12 myoblasts are positioned in the monomer solution with multiple optical traps at 1064 nm and then encapsulated by photopolymerization of monomer via projection of a 512x512 spatial light modulator illuminated at 405 nm. High 405 nm sensitivity and complete insensitivity to 1064 nm was enabled by a lithium acylphosphinate (LAP) salt photoinitiator. These wavelengths, in addition to brightfield imaging with a white light LED, could be simultaneously focused by a single oil immersion objective. Large lateral dimensions of the patterned gel/cell structure are achieved by x and y step-and-repeat process. Large thickness is achieved through multi-layer stereolithography, allowing fabrication of precisely-arranged 3D live cell scaffolds with micron-scale structure and millimeter dimensions. Cells are shown to retain viability after the trapping and encapsulation procedure.

8810-87, Session 17

Optical trapping and backaction in hollow photonic crystal cavities

Nicolas Descharmes, Ulagalandha Perumal Dharanipathy, Zhaolu Diao, Mario Tonin, Romuald Houdré, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No Abstract Available

8811-1, Session 1

Nanoscale confinement enables precision spectroscopy of biomolecules *(Invited Paper)*

Sabrina R. Leslie, McGill Univ. (Canada)

Imaging weak interactions and slow dynamics of biomolecules presents a challenge to existing single-molecule microscopy techniques. We dramatically improve single-molecule imaging by developing a new suite of devices which combine smoothly varying confinement with nanolithography. Using nano-positioners and microfluidics, we dynamically tune the chamber geometry and sample insertion, enabling enable precise and temporally resolved studies of molecular interactions under previously inaccessible conditions. In this talk, we report on the design and performance of a suite of new automated single-molecule imaging devices, suitable for a wide range of applications in biophysics, bioengineering, and materials science. Taking advantage of the continuum of applied confinement (from the nanometer to micron scale), we demonstrate precision spectroscopy of the confinement potential experienced by biomolecules. Further, we demonstrate the suitability of this system in sizing molecules and particles on the nanometer scale, which presents a challenge to existing approaches.

8811-2, Session 1

Characterization and manipulation of the secondary structure of surface-bound peptides *(Invited Paper)*

Lauren Webb, The Univ. of Texas at Austin (United States)

Proteins display a tremendous range of specific biological function. Applying this function to sensing, chemical catalysis, and biofuel generation would profoundly expand and change these traditional fields. This goal requires that the protein of interest be effectively integrated with inorganic materials such as a crystal surface in a controlled and oriented manner without altering its three-dimensional fold or compromising function, a challenging biomaterials problem. In the research described here, we chemically functionalize gold surfaces with peptides of known secondary structure. These surfaces are chemically characterized through X-ray photoelectron spectroscopy, ellipsometry, surface infrared spectroscopy, and scanning tunneling microscopy. Furthermore, we use surface infrared and circular dichroic spectroscopies to characterize the structure and orientation of the peptide on the surface. We demonstrate that correctly functionalized surfaces induce a alpha-helical secondary structure on a peptide that is disordered in solution. Demonstration of the control over a desired secondary structure of helical elements at a chemically functionalized surface is an important advance in preparing robust biologically mimetic surfaces and is expected to lead to an entirely new mechanism through which biological and inorganic materials can be coaxed to interact.

8811-3, Session 1

DLC coating in micro fluid channel with biochip

Ali S. Alanazi, King Saud Univ. (Saudi Arabia); Satoshi Murata, Kenji K. Hirakuri, Tokyo Denki Univ. (Japan)

Many polymers are applied to biomaterials by using the micro electro mechanical systems (MEMS) processing. SU-8 (acrylic-epoxy resin) is one of candidates for the photoresist materials in the nano-imprint lithography because of the workability, mechanical and photosensitive properties. It is required to miniaturize the biochip in various industry fields although the surface of the SU-8 is not enough to fit it to the biochip. The flow of the micro fluid in biochips should be controlled by changing the surface condition and structure of the channel. In order to make flat surface for smooth flow, diamond-like carbon (DLC) coating was carried out to the micro fluid channel with biochip because DLC has much attractive characteristics such as chemical inertness, low friction, biocompatibility, controllable wettability, optical transparency, and low surface roughness.

In biochip with SU-8 materials and Si substrate, DLC films have been prepared in the micro channel with the width size of 10 ?m by the photo lithography process. Radio frequency plasma enhanced chemical vapor deposition (rf-PECVD) technique is used for coating of the DLC film. DLC film has been investigated by Electron Dispersive X-ray spectroscopy (EDS), Scanning electron microscopy (SEM), Optical Raman spectroscopy, and contact angle measurement for wettability. In the EDS measurement, carbon peak around 4 keV was confirmed from the surface of the DLC coated channel. Sufficient adhesion between the DLC film and channel surface is obtained when coating condition of the DLC film was appropriately tuned. Wettability of the channel is also controllable from hydrophilic state to hydrophobic state by the selection of hydrophilic and hydrophobic DLC coating.

8811-4, Session 1

The method of capturing CO2 green house gas in cellulose matrix

Kwang Sun Kang, Kyungil Univ. (Korea, Republic of)

Reducing greenhouse gas has been important issue in recent years. Capturing CO2 gas in polymer matrix is attractive method to reduce the green house gas and use as a natural resource, such as polymer-CaCO3 composite. Calcium carbonate (CaCO3) and cellulose composite has been synthesized by bubbling CO2 gas into the mixture of cellulose acetate (CA) and Ca(OH)2 solution. Completely dissolved and transparent Ca(OH)2 solution was prepared to react stochiometric reaction of Ca(OH)2 and CO2. Since the strong absorption peak of the CA in infrared spectra, it is difficult to identify the existence of the CaCO3. To conform the existence of CaCO3 in the cellulose matrix, the CA was removed by dissolving and centrifuging the reaction composite. The characteristic absorption peaks of CaCO3 at 1450, 875 and 712 cm-1 were obtained for the residual composite. Field emission scanning electron microscope (FESEM) images show the shape and size of the CaCO3 particles in the cellulose matrix. Therefore, using cellulose and Ca(OH)2 matrix is one of the effective method capturing the CO2 green house gas.

8811-5, Session 1

H2O/D2O exchange in the presence of CO over SnO2 nanomaterials: operando DRIFTS and resistance study for gas sensor applications

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Modulation excitation DRIFTS together with resistance measurements have been carried out to study how the surface hydroxylation degree of SnO2 materials changes upon exposure to CO in air at 300oC and whether these changes correlate with the generation of free carriers.

We compare two materials synthesized via hydrothermal treatment and different only in their precursors: SnO2Ac synthesized from tin(IV) hydroxide acetate and SnO2Cl from tin(IV) chloride pentahydrate. DRIFTS and resistance measurements were performed simultaneously in an environmental chamber at 300oC and in a flow rate of 50 cm3/min. The experiments assumed consecutive 20 cycles of isotopic exchange: 1.3vol.% H2O was replaced with 1.3vol.% D2O in the background of pure air as well as in 100-500 ppm CO in air.

The materials were found to have similar particle sizes (16±7 nm), crystallite sizes (12±2 nm) and pore size distribution (16±1 nm). The biggest difference concerned the pore volume, which was about 40% higher for SnO2Ac. Sensor tests showed that the latter material, manifesting higher resistance change upon exposure to CO, also had better selectivity in the presence of water vapors. The reasons seem to stem from surface chemistry. In the case of SnO2 Ac, bridging ODs decreased upon exposure to CO at a rate similar to the resistance drop (240±50 and 200±30 ppm-1, resp.). For SnO2Cl no correlations were found between spectra evolution and resistance. Our results suggest that more basic character of surface OH groups on SnO2Ac results in the observed differences between the materials.

8811-6, Session 2

High efficiency solar water splitting with nanostructured oxide tandem cells *(Invited Paper)*

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A device that can convert solar energy into a chemical fuel with good efficiency while also offering high stability and the capability to be constructed with widely available materials using inexpensive processing techniques is urgently needed. Here we describe new advances that allow the construction of simple dual-absorber tandem cell using either Fe2O3 or WO3 as a photoanode. In order to give an insight into the electro-optical limitations and routes for improvement of these devices, the current-voltage characteristics as well as the spectral responses of the component parts, in addition to being measured in situ, are evaluated based on measured incident to photon efficiencies (IPCEs), transmittances of the photoanodes and photon flux on each active area. Finally, the actual performance of devices is evaluated and the highest-to-date solar-to-hydrogen conversion efficiency for dual-absorber oxide-based solar water splitting (3.1% overall) is reported.

8811-7, Session 2

Photoinduced processes in lead iodide perovskite sensitized solid-state solar cells

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Recently, a new type of solid-state mesoscopic heterojunction solar cell has been reported, employing nanoparticles of organometallic halide perovskites as the light absorbing material. This system was shown to provide remarkable solar conversion efficiencies, up to 9%, in conjunction with the well-known spiro-OMeTAD as the hole transport material.[1]

Remarkably, Lee et al. found that replacement of the mesoporous n-type TiO2 with insulating Al2O3 gave excellent power conversion efficiency, up to 10.9%.[2] The aluminum oxide being an insulator, no electron injection can happen from the perovskite to the metal oxide semiconductor, and the Al2O3 purely acts as a mesoporous scaffold for the perovskite/spiro-OMeTAD system.

The mechanistic processes in the device using mesoporous TiO2 are still under debate, as these organometallic halide perovskite cumulate both functions of light absorption and n-type conduction.

Herein we report an optical spectroscopy study of solid-state methyl ammonium lead iodide (CH3NH3)PbI3 based cells. Characterization of the material has been performed through integration sphere measurements and Photo-Induced Absorption Spectroscopy technique. Femtosecond Transient Absorption Spectroscopy and Terahertz Spectroscopy have been applied to both TiO2 and Al2O3-based cells in order to unravel the processes of charge separation and recombination following light absorption in the device. Luminescence of the perovskites was found to be one of the principal spectral features and its quenching could be correlated with the efficiency of the charge separation.

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8811-8, Session 2

High refractive index, solution processable molecular hybrid material targeted for use in photonic applications

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Photonics is an emergent area of interest in the scientific community in which solution processability offers many advantages over the often highly intricate protocols that are required for the manufacture of current technologies. In this work we demonstrate a solution processable molecular hybrid material whose tunable refractive index is used to produce one and two dimensional photonic structures such as distributed Bragg reflectors (DBRs) and waveguides respectively. We employ an organic/inorganic hybrid material, developed by Russo et al.: titanium oxide hydrate cross-linked polyvinyl alcohol (PVA). The material's refractive index can be tuned from 1.5 to greater than 1.8 by controlling the inorganic content of the material, yet without inducing significant optical losses. The properties of the material can be further modified after deposition: annealing can increase the refractive index to over 2.1. This shows that the refractive index of these hybrids can be tuned over a similar window as the best high index, organic materials previously reported. Furthermore, annealing of the material has been shown to affect the cross-linking behavior, allowing control of the interface dynamics of the inorganic species when depositing multi-layer structures. This makes patterning of the hybrid material's index in two, or possibly three, dimensions possible and therefore the production of waveguides, integrated optics and many other photonics applications.

8811-9, Session 2

Interfaces modulate open-circuit voltages of hybrid CH3NH3PbI3 perovskite/organic solar cells

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The deposition of a thin C60 (acceptor) layer in vacuum on methylammonium lead iodide (CH3NH3PbI3) (donor) perovskite creates a hybrid planar heterojunction for fabricating all-solid-state solar cells. Applying acceptor layer of varied lowest unoccupied molecular orbital (LUMO) level at the heterojunction interface modulates the open-circuit voltage (Voc) of CH3NH3PbI3 perovskites/organic hybrid solar cells. The CH3NH3PbI3/C60 hybrid solar cell exhibits the promising photovoltaic performance of open-circuit voltage VOC = 0.55 V, short-circuit current JSC = 5.21 mA/cm2, fill factor FF = 0.57, corresponding to a power conversion efficiency (PCE) of 1.6% under standard 1 Sun AM 1.5

simulated solar irradiation. The magnitudes of Voc and PCE elevate to 0.65 and 0.75 V, 2.4 and 2.1 % using [6,6]-phenyl C61-butyric acid methyl ester (PCBM) and indene-C60 bisadduct (ICBA), respectively. These results suggest that photovoltaic parameters of CH3NH3PbI3 perovskite/C60 or C60 derivatives cells are controlled by the level position offset of donor and acceptor. Additionally, applying an indium-tin-oxide (ITO)/glass substrate of the relatively higher work function improves the electrode interface and further elevates Voc of the hybrid cells. Voc of CH3NH3PbI3/PCBM cell elevates from 0.65 to 1.06 V. We report an optimized hybrid cell of Voc = 0.92 V, short-circuit current JSC = 7.93 mA/cm2, fill factor FF = 0.62, corresponding to a PCE of 4.5% under standard 1 Sun irradiation. Our findings demonstrate the design rules and the possible development of newly structured, hybrid, efficient solar cells.

8811-10, Session 3

Spectroscopic probes of transport and trapping in colloidal quantum dot photovoltaics

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High external quantum efficiencies have been obtained in the visible region in lead chalcogenide CQD photovoltaics. However, the corresponding efficiencies in the near-infrared lag behind because the thickness of CQD photovoltaic layers is limited by short carrier diffusion lengths. Time resolved infrared (TRIR) spectroscopy in conjunction with electrical characterization methods are used to demonstrate twenty-fold enhancement of the mobility-lifetime products of minority carriers in PbS CQD films passivated with various ligands. Mid-infrared electronic transitions measured by TRIR spectroscopy provide information about charge trap densities and energetic distributions. Direct observation of the vibrational features of ligands attached to surface trap states provide unique insights into the nature of charge traps and helps define pathways for their elimination. These findings demonstrate that TRIR spectroscopy provides a means to directly probe the electronic properties of charge trap states and the underlying ligand-nanocrystal interactions that give rise of those states.

8811-11, Session 3

In-situ investigation of adsorption of dye and coadsorbates on TiO2 films using QCM-D, fluorescence and AFM techniques

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Recently, dye-sensitized solar cells have achieved a record power conversion efficiency of 13.1% (0.5 sun) and 12.3% (1 sun) using a Co(II/III)tris(bipyridyl)–based redox electrolyte in conjunction with donor - π-bridge – acceptor (D-π-A) zinc porphyrin dye as sensitizer (YD2-o-C8) and Y123 as cosensitizer.(1) Beyond panchromatic light harvesting, new sensitizers have to comply with one-electron redox couples that not only allow for high photovoltage, but also entail the challenge of fast recombination with photoinjected electrons from the TiO2 conduction band. The improvements in photocurrent and photovoltage are assumed to be due to better packing of dye molecules on the TiO2 surface. Yet we know alarmingly little about the dynamics of dye adsorption, self-assembly of the monolayer, and formation of multilayers or aggregates. In addition, several reports have pointed out the role of molecular coadsorbates like chenodeoxycholic acid that positively affect interfacial recombination and reduce aggregation.

Herein, we use a quartz crystal microbalance with dissipation technique (QCM-D) to study dynamically and quantitatively dye sensitization of TiO2 in situ.(2) We studied dye loading for a Ru(II) polypyridyl complex (Z907), of a triphenylamine-based D-π-A dye (Y123), and of a state-of-the-art porphyrin sensitizer (YD2-o-C8). By combining the QCM-D technique with fluorescence measurements, we quantify molar ratios between the above dyes and various coadsorbates like chenodeoxycholic acid and CTAB. Furthermore, we will present first studies using liquid-phase AFM on the adsorbed dye monolayer, thus obtaining complementary microscopic information that may lead to understanding of the adsorption mechanism on the molecular scale.

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8811-12, Session 3

Exciton dynamics in colloidal CdSe/CdS core-shell nanostructures

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We have studied excitons in films of colloidal CdSe/CdS nanorods that produce efficient LED in the visible region. These samples feature strong oscillator strength of optical transitions, which make these materials promising for a range of further photonic devices such as classical (photon) lasers and polariton emitters. We have performed temperature-dependent steady-state photoluminescence experiments. The CdSe/CdS nanorod photoluminescence intensity displays strong temperature dependence, with increasing intensity with increasing temperature, and the maximum emission energy exhibits a temperature-dependent blue shift. This maximum shifts from 2.06 eV at 290 K to 2.13 eV at 10 K, which represents a shift of 67 meV. We attribute this shift to the interaction of the exciton with the interface that creates excitonic traps at lower energies. As the temperature rises, thermally activated detrapping for temperatures above 38 K. Such detrapping processes rationalise the counterintuitive increase of photoluminescence intensity with temperature. In this presentation, we will discuss trapping and detrapping dynamics. Furthermore, we will address the role of coherence in determining early-time exciton dynamics, and its effect on exciton surface trapping, by means of ultrafast phase-locked two-pulse coherent studies, in which the time-integrated photoluminescence spectral intensity is measured as a function of delay and relative phase between the phase-locked pulses.

8811-13, Session 3

Modulation of silicon by (multi-)interfaces and by local nanostructurations leading to a new specific phase of material (metamaterial) for light-to-electricity conversion

Zbigniew T. Kuznicki, Univ. de Strasbourg (France)

Because Si is, and undoubtedly will remain, a basic material for converting light into electricity, challenging research has been underway for years to overcome innate optoelectronic constraints of its indirect bandgap. Exploiting soft photon-electron-electron interactions to add to the well characterized hard photon-matter interactions offers one possible area where conversion efficiency might be improved. Following this approach, we have found that a Si-derived metamaterial obtained by multiple nanotransformations, leading to a nanoscale Si-layered system with multiinterface interactions, can furnish low-energy mechanisms. The energy flow starts with the incoming light (h ≥ 1.40 eV) being transformed by different superposed nanosystems. The design of these multiinterface devices had to take into account several interrelated mechanisms intervening in the light-to-electricity conversion. This structure forms the basis of a multistage conversion cycle observed for the first time that depends on interactions of hot electrons with active interfaces and conditioned crystalline defects transformed into Si metamaterial units that we call "segtons" (unity for secondary electron generation tuned on nanoscale). We will describe the background, modeling and complete 1D simulations of all optoelectronic features of this new cell. Simulations and experimental data coincide almost perfectly. Thus a useful exploitation of energetic photons seems to be possible due to a multiple generation of secondary electrons with a low characteristic energy, whereas today a large part of an energetic photon's energy is wasted on device heating. With the additional carrier generation per absorbed photon, the efficiency of these cells can be said to result from giant photoconversion.

8811-14, Session 4

Relation of structure and charge transport in 'single-stack' organic nanowires *(Invited Paper)*

Holger Frauenrath, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Organic nanowires may provide insights into the fundamental processes of charge generation and transport in organic semiconductors under nanoscopic confinement. Here, we demonstrate how a simple molecular design results in nanowires with defined lateral dimensions that comprised a single stack of tightly π–π stacked chromophores at their core. Moreover, we prepared well-defined microfibers that exhibited hierarchical structure formation with a remarkably high degree of internal order and enabled us to obtain detailed structural information on all length scales with molecular level precision. The nanowires and microfibers nanowires showed light-induced formation of radical cations that behaved like positive polaron charge carriers. The nanofibrils were semiconducting, showed space-charge injection-limited conductivity behavior, and exhibited photo-current generation, relating their macroscopic electric properties to the spectroscopically characterized charge carriers. Our results, thus, provide an example of a universal organic nanowire model system that successfully links molecular design, well-defined supramolecular structure formation, charge carrier generation, and finally macroscopic charge transport.

8811-15, Session 4

Organic nanostructures for plastic electronics: control and characterisation *(Invited Paper)*

Ji-Seon Kim, Imperial College London (United Kingdom)

Organic semiconductors such as small molecules and conjugated polymers have been demonstrated as the active material in various optoelectronic and electronic devices including light-emitting diodes, transistors, and photovoltaic cells. For these organic semiconductor devices, a great deal of the physics occurs at the organic-organic interfaces. Therefore, understanding the organic-organic interfaces, in particular in terms of the structure-property relationships of nanostructures in thin films, is essential in designing efficient and stable devices. In this talk, the role of these organic nanostructures, with an important focus on molecular-scale electronic structures and electronic processes across these nanostructures will be discussed. In particular, the effects of degree of local molecular order, thin film morphology and nature of interfaces on the optoelectronic and charge transport properties will be addressed. As one of the most valuable characterisation techniques for organic nanostructures, we have extensively used Raman spectroscopy. Raman spectroscopy is a non-destructive technique which can deliver valuable chemical/ structural information together with optical properties of materials with sub-micrometer spatial resolution from surface films as well as from buried layers in the devices. We will show some examples of our Raman studies performed on various organic nanostructures in thin films and devices [1-8]. The application of non-resonant, resonant and polarized Raman spectroscopy to the characterisation of reaction, composition, crystallinity and orientation of molecules will be also discussed.

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8811-16, Session 4

Designing hybrid nanocolloids for nanothermy and multimodal imaging

Pascal André, Univ. of St. Andrews (United Kingdom) and RIKEN (Japan); Chen Shu, Univ. of St. Andrews (United Kingdom); C. Hoskins, Lijun Wang, Michael P. MacDonald, Institute for Medical Science & Technology (United Kingdom) and Univ. of Dundee (United Kingdom)

Multimodal nanoparticles (nPs) are a growing component of biomedical research activity with for instance dual imaging demonstration taking advantage of designing nanoparticles with combined optical and magnetics properties.[1]

Stepping aside of imaging we have recently demonstrates that hybrid nanocolloids can be designed and used to create nanoprobes for remotely sensing temperature of aqueous media. Such multi-modal nanocolloids combine development opportunities not only for multimodal magnetic-optical imaging but also for non-invasive and remote absolute temperature optical monitoring suitable for hyperthermia treatments and cell poration.

Along the potentials associated with combining several properties within a single nanocolloid, the presentation will build on and discuss the synthesis and characterization of biocompatible FePt nPs suitable for biomedical applications.[2,3]

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8811-17, Session 4

Covalent functionalization of carbon nanotubes and its effect on transport properties

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Covalent chemistry on carbon nanotubes generates stable functionalities that are valuable for improving their processing and tailoring their affinity with other molecules. However, the covalent bonding deeply alters the nanotubes electronic properties, which is a critical drawback for device applications. We first describe how the addition of monovalent groups affects the transport properties of single-walled carbon nanotubes (SWNTs), and we discuss the underlying mechanism and its reversibility. We then introduce two new approaches that allow extensive covalent functionalization of carbon nanotubes without compromising on their electronic properties. For each case, we demonstrate the fabrication of functional carbon nanotube devices. First, double-walled carbon nanotubes (DWNTs) are functionalized using a monovalent reaction with aryldiazonium salts. Absorption and Raman spectroscopy along with electrical measurements are performed to show that functionalization occurs strictly on the outer wall and preserves the optical and transport properties of the inner wall. Functionalized-DWNT devices are shown to operate with similar characteristics as pristine single-walled carbon nanotube devices [1]. Second, SWNTs are functionalized with a different type of addends using a carbene reaction, which forms a divalent bond with the nanotube surface. For both metallic and semiconducting species, electrical measurements performed on a large number of functionalized and unfunctionalized SWNT devices show identical characteristics [2].

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8811-18, Session 4

Probing the transient fate of C-N bonding in hydrazine-treated carbon nanotubes by synchrotron photoelectron spectroscopy

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The properties of hydrazine-treated carbon nanotubes (CNTs) were investigated by synchrotron photoelectron spectroscopy. The surfactant-free CNTs used in this study were synthesized by alcohol catalytic chemical vapor deposition. When the CNTs subject to the vapor-phase hydrazine treatment and the 80ºC-baking treatment were probed by ultraviolet photoelectron spectroscopy (UPS), the results showed (i) damaged π-bonding and (ii) the shift of the CNTs' Fermi level toward the conduction band. A further 350ºC-baking treatment on the hydrazine-treated CNTs could restore the damaged π-bonding and cause the CNTs' Fermi level to shift back toward the valence band. The results obtained from UPS indicated that the above interaction between hydrazine and CNTs was a thermally metastable chemical adsorption. When the CNTs subject to the vapor-phase hydrazine treatment and the 80ºC-baking treatment were probed by X-ray photoelectron spectroscopy (XPS), the results showed a significant increase in the spectral intensity of the signal corresponding to C-N bonding in the XPS profile. A further 350ºC-baking treatment on the hydrazine-treated CNTs could essentially eliminate the spectral intensity of the signal corresponding to C-N bonding in the XPS profile. Our experimental results show that the transient fate of the thermally metastable C-N bonding is associated with the nitrogenous radicals, such as nitrene and amidogen, thermally decomposed from hydrazine. The chemical association of nitrogenous radicals with CNTs generates metastable amino/aziridino derivatization on the surface of CNTs, which will disrupt the continuum of CNTs' graphitic domains. Upon further baking, the disruptive functionalization can be eliminated to restore the graphitic sp2-carbon bonding structure.

8811-19, Session 4

Fabrication of nanoparticle single-electron transistors and photoinduced modulation in the charge transport property

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Metal and semiconducting nanoparticles (NPs) have attracted significant attention because of their excellent properties and potential applications in bottom-up electronics. To examine the charge transport properties of single or small number of such NPs and their interactions with external stimuli, single-electron transisotor (SET) strucures can be a powerful tool. We report here fabrication of Au- and CdSe/ZnS-NP SETs and their charge transport properties. Remarkably, we have demonstrated a method to modulate the transport properties by molecular doping followed by light irradiation.

Nanogap electrodes on the SiO2 (50 nm)/p-deped Si substrate were formed by an electromigration method. Au- and CdSe/ZnS-NP (6 nm in diameter) were adsorbed on the electrode through octanedithiol. Copper phthalocyanine (CuPc) was then evaporated submonolayer on the Au-NP devices to induce a photoresponse. The charge transport properties and their photoresponse were meausred at 13 K.

We successfully observed Coulomb diamond originated from single-electron transport in the Au- and CdSe/ZnS-SETs. In the Coulomb diamond of CdSe/ZnS-SET, a large conductance gap appeared probably due to the energy gap of CdSe/ZnS NP. In charge transport properties of the CuPc-doped Au-SETs, conductance switching was observed between two specific states induced by light irradiation and applied voltages. We also examined the current response at a constant drain voltage under light irradiation. The current fluctuation was induced by the light irradiation, especially at 550 to 700 nm corresponding to the optical absorption band of CuPc. A change in the potential of Au-NP is responsible for conductance switching, and is resulted from photoinduced charging of CuPc.

8811-20, Session 5

Interfacial modification for organic electronic applications *(Invited Paper)*

Seth R. Marder, Stephen Barlow, Jean-Luc Brédas, Jared Delcamp, Anthony J. Giordano, Song Guo, Bernard Kippelen, Hong Li, Swagat Mahopatra, Sergio A. Paniagua, O'Neil Smith, Yadong Zhang, Georgia Institute of Technology (United States); Antoine L. Kahn, Yabing Qi, Wei Zhao, Princeton Univ. (United States)

Organic semiconductors have attracted interest for electronic applications due to their potential for use in low-cost, large-area, flexible electronic devices. Here we will report recent developments pertaining to surface modifiers and dopants that could impact the charge collection processes in organic light emitting diodes, organic field effect transistors, and organic photovoltaic devices. In particular, we will examine how phosphonic acids assemble on ITO substrates, the impact of the surface dipole on the work function of the ITO and electron transfer kinetics across surface modifiers. We will also discuss the development of metallocene based dimers as n-dopants and Molybdenum as p-dopants for organic semiconductors and their impact on device performance.

8811-21, Session 5

Electronic structure of conducting oxide-organic and organic-organic interfaces of relevance to OLED and OPV devices *(Invited Paper)*

Jean-Luc Bredas, Georgia Institute of Technology (United States)

In this presentation, we intend to cover two main topics:

(i) The electronic structure at interfaces between a conducting oxide electrode or interlayer and an organic layer, such as those found in organic light-emitting diodes and solar cells. In particular, we will discuss the mechanism by which self-assembled (mono)layers can modify the electrode work function of the conducting oxide electrode and the interfacial energy-level alignment. These parameters directly impact the charge-injection barrier [1].

(ii) The organic-organic interface. We will describe our recent progress in the description of the structural configurations at the interface between the donor and acceptor components in an organic solar cell and the impact that variations in these configurations have on the nature of the interfacial charge-transfer states [2].

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8811-22, Session 5

Photo-induced charge transfer across an organic /contact interface: polaronic state spectroscopy

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Photo-induced charge transfer across an organic / contact interface: polaronic state spectroscopy

Photo-induced charge transfer from an Indium Tin Oxide (ITO) contact into [6,6]-phenyl-C61-butyric acid methyl ester (PC60BM) and [6,6]-phenyl-C71-butyric acid methyl ester (PC70BM) is measured using capacitive photocurrent spectroscopy. PC60BM is drop cast onto an ITO coated glass slide, which is affixed to a copper block inside an evacuated optical cryostat. A current amplifier is connected between the ITO layer and the copper block and the ac photocurrent is monitored as the ITO / PC60BM interface is exposed to light from a tunable pulsed laser source. Optically generated electron-hole pairs separate across the PC60BM / ITO interface, under the force of an applied dc potential combined with any built-in potential due to trapped charged and the difference in electron affinity between PC60BM and ITO. Charge transfer peaks are observed for a series of excitation energies below the PCBM absorption edge. To demonstrate that charge transfer is necessary to observe the CPS signal, measurements were performed on samples containing an LiF insulating layer separating the PC60BM and ITO. The current drops off exponentially with LiF thickness, as would be expected for Fowler-Nordheim tunneling through the insulating barrier. Bias dependent measurements indicate that the capacitive photocurrent signal is due to negative charge transfer from the ITO into the PC60BM. The observed transitions are similar to those predicted by theoretical calculations of the absorption spectra for negatively charged c60 and c70 chains. This suggests that charge transfer occurs preferentially at the poloronic transition energies in the PCBM, providing a means for polaronic state spectroscopy.

8811-23, Session 6

Energy level pinning and electric field distribution at organic/inorganic interfaces *(Invited Paper)*

Norbert Koch, Humboldt-Univ. zu Berlin (Germany) and Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

Inducing Fermi-level pinning in an organic semiconductor at the interface to another material results in accumulation or depletion of electrons at the interface. Examples for the resulting band-bending at pinned organic/electrode interfaces and organic/inorganic semiconductor heterojunctions will be introduced. The key roles of inorganic semiconductor surface termination and doping level on level pinning will be discussed. The energy level alignment at organic/organic semiconductor heterojunctions is essentially independent of deposition sequence, as long as supporting electrodes do not induce energy level pinning. When the energy levels become Fermi-level pinned due to an initial electronic non-equilibrium situation, long-range charge transfer can result. This creates an electric field right at and beyond the heterojunction. This effect is exemplified for prototypical donor and the acceptor interfaces, which are relevant for photovoltaic cells. Furthermore, it is demonstrated that light absorption induced charge separation at an organic heterojunction can be measured directly with photoemission spectroscopy.

8811-24, Session 6

Energetics and dynamics in organic photovoltaics: the role of the contacts *(Invited Paper)*

Erin L. Ratcliff, The Univ. of Arizona (United States); Sarah R. Cowan, National Renewable Energy Lab. (United States); Brian Zacher, Jeremy L. Gantz, The Univ. of Arizona (United States); Dana C. Olson, National Renewable Energy Lab. (United States)

The primary function of the contacts in organic photovoltaics is efficient extract of charges while maintaining the open circuit voltage (VOC) through Fermi level offsets. In bulk heterojunction organic photovoltaics, surface recombination and loss mechanisms, including leakage, decrease power conversion efficiencies. It is well understood that implementation of the selective interlayers can be used to mitigate leakage of undesired charges across the active layer/contact interface. Thermodynamic selectivity for holes (electron blocking) is obtained using a material with a work function at or greater than the charge transport level for holes and a conduction band closer to vacuum than the transport level for electrons. However, little is understood about how the device performance is influenced by the hole-collection rates at the interlayer/active interface, relative to rates of recombination. Time-delay collection field measurements may be used to measure charge extraction and recombination dynamics in organic photovoltaics. An initial voltage is applied near VOC and carrier density is controlled via a white light bias. A nanosecond laser pulse is used to perturb the system and generate excess charges, which will either recombine or be extracted using an extraction voltage after a known time delay from the laser pulse. By monitoring the dynamics of the carriers as a function of applied voltage, background white light bias, and fluence from the laser pulse, we are able to isolate differences in recombination and extraction rates as a function of the selectivity of the contact.

8811-25, Session 6

Work function and open circuit voltage modulation via self-assembled interface modification of zinc oxide electron collection layer in polycarbazole-based organic solar cells

Sarah R. Cowan, National Renewable Energy Lab. (United States); Philip Schulz, Princeton Univ. (United States); Erin L. Ratcliff, The Univ. of Arizona (United States); Andres Garcia, National Renewable Energy Lab. (United States); Anthony J. Giordano, Georgia Institute of Technology (United States); Stefan Oosterhout, Bradley A. MacLeod, David S. Ginley, National Renewable Energy Lab. (United States); Seth R. Marder, Georgia Institute of Technology (United States); Antoine L. Kahn, Princeton Univ. (United States); Dana C. Olson, National Renewable Energy Lab. (United States)

Zinc oxide (ZnO) is a low-cost semiconductor made from earth-abundant materials; multiple routes to sol-gel processing enable the formation of thin films, making the material a promising candidate for an electron collection layer for next-generation thin-film photovoltaics. However, previous research has observed ZnO to be easily etched via a number of simple solvents. Degree of crystallinity, exposed crystal face, sol-gel precursor, and thermal treatment all play a role in determining thin film chemical resistance of zinc oxide. Poor chemical resistance has minimized work function modification of ZnO via dipole interface modifiers such as benzyl phosphonic acid (BPA), shown to modify the work function of ITO and to modulate the open circuit voltage in full devices. We demonstrate that work function modification of the ZnO interface via spincast dipole interface modifiers translates into a proportional modulation of the open circuit voltage in BHJ solar cells. Spincasting minimizes exposure of the ZnO to the acidic solution, allowing reproducible, non-destructive deposition, as assayed by XPS, PM-IRRAS, and UPS / IPES of modified ZnO. Modulation of the work function and evidence of charge transfer is shown by UPS of thin films of polymer bulk heterojunction on cast onto ZnO modified by the self-assembled BPA dipole. The deposition of BPAs is shown here to increase the open circuit voltage and to have no impact on the lifetime of poly[N–9'-hepta-decanyl-2,7-carbazole-alt-5,5-(4',7'-di-2-thienyl-2',1',3'-benzothiadiazole)] (PCDTBT) : [6,6]-phenyl C71-butyric acid methyl ester (PC70BM) inverted devices over the testing period of 30 days storage in air.

8811-26, Session 6

A convenient solution processing route to high mobility CdS films

Bright J. Walker, Ulsan National Institute of Science and Technology (Korea, Republic of)

Solution-processed CdS field effect transistors (FETs) and solar cells are demonstrated via the spin-coating and thermal annealing of soluble cadmium thiolate compounds. The synthesis is carried out in one simple step using cadmium oxide and tertiary alkane thiols. The cadmium thiolates are soluble in organic solvents such as chloroform and may be spin-coated, like organic semiconductors, to form thin films. The cadmium thiolate films decompose rapidly at 240 oC to yield semiconducting cadmium sulfide films. Field effect transistors are easily fabricated using these films and exhibit electron mobilities of up to 64 cm2 V-1 s-1, which compare favorably to FETs prepared from other solution-processed materials such as organic semiconductors, inorganic nanoparticles or chalcogenide films. Initial attempts to prepare hybrid, bilayer solar cells were successfully realized by spin-coating a p-type semiconducting polymer layer on top of the n-type CdS film. These devices show significant photocurrent response from both the CdS and polymer layers, indicating that the CdS films are able to participate in photo-induced electron transfer from the polymer to the CdS layer as well as photo-induced hole transfer from CdS to the polymer layer.

8811-27, Session 7

Electronic properties of cationic narrow band gap conjugated polyelectrolytes *(Invited Paper)*

Jung Hwa Seo, Dong-A Univ. (Korea, Republic of)

We report the design, synthesis, optical and electronic properties of two novel narrow band gap conjugated polyelectrolytes (NBGCPEs) based on a poly[2,6-(4,4-bisalkyl-4H-cyclopenta-[2,1-b;3,4-b']-dithiophene)-alt-4,7-(2,1,3-benzothiadiazole)] donor-acceptor backbone. A comparison to the properties of the neutral precursor material shows that the ionic component in these cationic NBGCPEs leads to a red shift in the absorption spectra and to a modification of the polymer electronic energy levels. Both the HOMO and the LUMO are lowered in energy, with the net effect being dependent on the choice of counterion, i.e. bromide vs. tetrakis(1-imidazolyl)borate. Moreover, we find the unexpected observation of n-type transport in thin film transistors, which differs from the widely studied p-type transport in neutral systems with isoelectronic backbones. These observations lead one to conclude that unique opportunities for materials design are possible upon introduction of ionic functionalities adjacent to semiconducting polymers that exhibit charge transfer excitations.

8811-28, Session 7

Charge transport and recombination in organic light emitting transistors *(Invited Paper)*

Ebinazar B. Namdas, The Univ. of Queensland (Australia)

Light emitting field effect transistors (LEFETs) are a class of next generation devices which combine the switching properties of field effect transistors (FET) with light emitting capabilities of organic light-emitting diodes (OLEDs) in a single device architecture. LEFETs have significant potential in a number of applications such as active matrix displays, sensors, and even in electrically pumped lasers. However, current LEFET architectures suffer from inefficient charge injection of electrons and holes from opposite source and drain electrodes, leading to unbalanced charge transport and hence poor device performance. This talk will show our recent progress in the design and fabrication of high-performance solution-processed LEFETs. Comparative studies will be presented over a wide range of device architecture, including novel materials. On the basis of these data, I will address the parameters that influence charge injection, charge transport and recombination processes in these devices. State-of-the-art materials, design and performance will be presented and discussed in this talk.

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8811-29, Session 7

Using EGaIn to uncover new phenomena in molecular tunneling junctions

Davide Fracasso, Univ. of Groningen (Netherlands)

This talk focuses on charge transport studies using Eutectic Gallium Indium (EGaIn), a method that we introduce in 2008[1], to reveal intrinsic properties of molecules into SAMs.

The ability to control the flow of charge at the quantum level through organic synthesis is a tantalizing prospect that draws researchers from myriad sub-disciplines of chemistry and physics to molecular electronics (ME).

Chemistry is replete with cases where seemingly minor changes in the chemical structure of a molecule result in significant changes in a physical property of the system.

Particularly conjugated molecules are interesting since relationship between parts of the molecules and physical properties can be found.

In a earlier work we did, for the first time, show evidence of quantum interference (i.e., the influence of conjugation patterns) in tunneling junctions comprising SAMs of aryethynylene thiolates using EGaIn as a conformal top-contact[2]. We found good qualitative agreement between experiment and theory.

In a more recent work we could demonstrate that EGaIn can resolve the differences between SAMs that differ by only a single atom. This sensitivity is made possible by the collective properties of the molecules in the SAMs (e.g., torsional angles) and is therefore an intrinsic property of the SAMs; we would not expect the same results from tunneling experiments on single molecules.

For these reasons mentioned above and more, EGaIn has been recognized as a new ease molecular electronics tool.

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8811-30, Session 7

Electrolyte-gated transistors based on light-emitting solution-processable films

Jonathan J. Sayago, Ecole Polytechnique de Montréal (Canada); Yuvaraj Sivalingam, Univ. degli Studi di Roma Tor Vergata (Italy); Mitesh Patel, Fabio Cicoira, Clara Santato, Ecole Polytechnique de Montréal (Canada)

Organic Field Effect Transistors (OFETs) are the key elements for low-cost flexible electronics, such as flexible displays, sensor arrays and radio frequency identification tags [1,2]. The replacement of conventional gate dielectrics (e.g. SiO2) with an electrolyte gating media is an effective approach to induce high charge density, in the transistor channel, upon application of low electric bias [3,4]. We report on electrolyte-gated transistors based on thin light-emitting films of organic polymers, such as poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene], or metal oxides, such as zinc oxide. As the electrolytes different ionic liquids were considered, based on 1-butyl-3-methylimidazolium [BMIm] or 1-ethyl-3-methylimidazolium [EMIm] as the cation, and bis(trifluoromethylsulfonyl) imide [TFSI] or hexafluorophosphate [PF6] as the anion. The light-emitting properties of the films in contact with the ionic liquids were investigated, in inert atmosphere. The transistor electrical characteristics were correlated to the ionic conductivity, viscosity and ion size of the electrolyte.

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8811-31, Session 7

Effect of film nanostructure on in-plane charge transport in organic bulk heterojunction materials

Eric Danielson, The Univ. of Texas at Austin (United States); Zien Ooi, A*STAR Institute of Materials Research and Engineering (Singapore); Ananth Dodabalapur, The Univ. of Texas at Austin (United States)

Charge transport parameters of organic bulk heterojunction (BHJ) materials are greatly affected by the nanomorphology of these materials. A complete understanding of this relationship is needed to design organic photovoltaic (OPV) devices with high power conversion efficiencies. Parameters such as carrier mobilities, carrier concentrations, and the recombination coefficient have traditionally been successfully measured using vertical structures similar to organic photovoltaic (OPV) cells. We have developed a lateral BHJ device which complements these vertical techniques by allowing spatially resolved measurement along the transport direction of charge carriers. This is essential for evaluating the effect of nanoscale structure and morphology on these important charge transport parameters. Nanomorphology in organic BHJ films has been controlled using a variety of methods, but the effect of these procedures has been rarely correlated with the charge transport parameters of the BHJ material. Electron beam lithography has been used to create lateral device structures with many voltage probes at a sub-micron resolution throughout the device channel. By performing in-situ potentiometry, we can determine both carrier mobilities and valuable information about the recombination mechanism and coefficient. Spin coated and inkjet printed P3HT:PCBM films are measured using these lateral devices to determine the effect of solvent additives such as DIO, the P3HT:PCBM weight ratio, and the annealing methodology. These measurements are correlated with the observed effect on the film nanostructure, obtained from AFM imaging.

8811-34, Session 8

The local enviroment affects the exciton dynamics in Rubrene single crystals

Bjorn Gieseking, Teresa Schmeiler, Benjamin Muller, Carsten Deibel, Bernd Engels, Vladimir Dyakonov, Jens U. Pflaum, Julius-Maximilians-Univ. Würzburg (Germany)

As for its inorganic counterparts the future developments in organic electronics are driven by an advanced device miniaturization. Therefore, the opto-electronic behavior of up-to-date devices is progressively governed by the local structural environment. However, there is a lack of organic semiconductor materials providing access to the fundamental structure-functionality relation, either due to limitations by their inherent growth or their optical characteristics.

In this work we present a systematic investigation of the optical states, so-called excitons, and their temporal evolution in the prototypical organic semiconductor rubrene by means of time and temperature dependent photoluminescence studies. This material offers the unique possibility of preparing well-defined morphologies with adjustable degree of confinement. By this approach we are able to confirm the direct influence on the temperature dependent optical processes with picosecond resolution already for a spatial localization of excitation on the µm length scale. While in bulk single crystals the exciton decay dynamics are governed by thermally activated singlet fission, excitons created in microcrystals are trapped by dark states localized on the surface and leading to a pronounced enhancement of their average lifetime.

Our results highlight the impact of the local environment on the excitonic states and their dynamics in organic semiconductors. With respect to the spatial dimensions of organic thin film devices, this correlation and the reported effects emerging by the confinement have to be considered upon further miniaturization and in the development of innovative device concepts, such as photovoltaic cells based on triplet-harvesting.

8811-35, Session 8

Photoexcitation and photochemical stability of organic photovoltaic materials from first principles

Na Sai, The Univ. of Texas at Austin (United States); Kevin Leung, Sandia National Labs. (United States)

The development of high efficiency organic photovoltaics (OPV) has recently become enabled by the synthesis of new photoactive materials including, e.g., the lower band gap conjugated polymers that allow light absorption over a broader range of the spectrum. On the other hand, stability of these new polymers, a key requirement for commercialization, has not yet received sufficient attention. Here, we investigate the material stability and degradation mechanisms in OPV materials with the hope to discover OPV candidate materials with improved photochemical stabilities. We report first-principles theoretical modeling of photo-induced degradation of OPV polymers carried out using ab-initio density functional theory and quantum chemistry methods. We report photooxidation routes and reaction products for reactive species including superoxide oxygen anions and hydroxyl groups interacting with the standard workhorse OPV polymer, poly(3-hexyl-thiophene) (P3HT). We discuss theoretical issues and challenges affecting the modeling such reactions in OPV polymers. We also discuss the application of theoretical methods to low-band-gap polymers, and in particular, the effect of the incorporated silicon atom on the photoexcitation and photochemical reactions in these new polymers.

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8811-37, Session 8

The principles of manipulating the phase transformations and solid-state order of organic semiconductors to and its effects on their photophysical properties

Natalie Stingelin-Stutzmann, Imperial College London (United Kingdom)

We will present a survey on the principles of how to manipulate the phase transformations and solid-state order of organic semiconductors to tailor and manipulate their final "morphology" from the liquid phase targeted towards technological and practical applications. Focus will be on how microstructural changes affect the electronic landscape in this class of materials, including charge generation, charge recombination and photovoltaic processes in general. We will show, for instance, that the evolution of a semicrystalline structure with well-defined interfaces between amorphous and crystalline domains of the polymer is required for spatial separation of the electron and hole. This structural characteristic largely controls the yield of free charges, but also serves as a recombination center where mobile holes encounter a bath of dark electrons resident in the amorphous phase and recombine with quasi first-order kinetics. We will present in addition a range of photophysical, electrochemical and physicochemical data that provide evidence that formation of a crystalline phase of at least one component is necessary for driving the spatial separation of photogenerated charges. We discuss this on the example of the fullerene component and demonstrate that its crystallisation results in an increase in electron affinity, providing an energetic driving force for spatial charge separation.

8811-54, Session 8

THz time domain spectroscopy of charge carrier dynamics in conjugated polymers

Mariateresa Scarongella, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Understanding the process of charge generation in polymer:fullerene bulk heterojunction (BHJ) blends is the key to improve the efficiency and the performance of organic solar cells1. There is still a lot of debate about the origin of free charges inside the blended materials. According to a simple picture, the exciton after travelling to an interface, undergoes charge separation to a Coulomb bound charge-transfer state which relaxes in 100 fs to its lowest vibrational level. After a time scale of 5 ns the bound charges can geminately recombine or completely separate to the polymer and fullerene phases2. Recently a more complex mechanism has been experimentally proven: the free charges are created after exciton quenching in a time shorter than 100 fs from hot delocalized charge transfer states before relaxation2,3. The charge separation happens in a mixed phase where the polymer and the fullerene are not pure and completely separated4. THz time domain spectroscopy gives information on the lifetime of generated charge carriers and on recombination dynamics. Specifically, it is more selective to detect the contributions of free charges with femtosecond time resolution. However, this technique also allows us to have access to the spectrally resolved photoconductivity, from which it is possible to distinguish between the presence of bound charges (in the exciton or charge transfer state) and free charges. In particular, we studied thin films of neat and blended (with fullerene) conjugated donor?acceptor copolymers, changing the excitation wavelength and the laser intensity.

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8811-36, Session 9

Femtosecond stimulated resonance Raman study of excited state reorganization in organic semiconductors *(Invited Paper)*

Sophia C. Hayes, Univ. of Cyprus (Cyprus)

Understanding the ultrafast dynamics of electronic excited states of π-conjugated oligomers and polymers is of fundamental importance in chemical physics to underpin the design of next generation polymeric semiconductors for applications in optoelectronics. A direct probe of structural changes that eventually dictate the dynamics e.g. governing power conversion efficiencies in solar cells is essential for such understanding. Femtosecond Stimulated Raman (FSRS) spectroscopy offers a unique time-resolved Raman probe that has been used in recent years in time-resolved studies of ground and excited states, offering a great alternative to traditional Raman scattering methods, especially for fluorescent samples. The major advantage of FSRS is its ability to follow early-time (tens of femtoseconds) structural dynamics with mode-specific resolution (~15 cm-1), thus constituting it a powerful method for the investigation of excited state structure and dynamics in π-conjugated materials. Furthermore, the experimental setup allows for simultaneous collection of FSRS spectra of the excited state and transient absorption (TA) dynamics, which provides a direct correlation of excited state absorption changes to structural changes in oligomers/polymers. Here, we will exemplify the power of this spectroscopic method to elucidate excited state reorganization using known oligomeric/polymeric systems as models.

8811-38, Session 9

Synthesis and characterization of 3,4-ethylenedioxythiophene and 2-(3-thienyl) ethanol copolymer

Shuyun Zhou, Technical Institute of Physics and Chemistry (China)

The chemical polymerizations/copolymerizations of thiophene derivatives have been widely investigated in polymer field and many derivatives of polythiophene have been prepared in the past few decades. As a representative derivative of polythiophene, poly(3,4-ethylenedioxythiophene) (PEDOT) has been utilized in a large variety of applications due to its excellent characteristics. However, the extensive applications of PEDOT have been limited because of its poor solubility and adhesion. It's known that the involved functional groups in the polymer can greatly affect the properties of the chain, such as hydroxyl. In order to improve the performances of PEDOT, the copolymerization between 3,4-ethylenedioxythiophene (EDOT) and 2-(3-thienyl) ethanol had been adopted, and a new copolymer poly[(3,4-ethylenedioxythiophene)-2-(3-thienyl) ethanol] had been synthesized via the traditional chemical polymerization. In this study, the 2-(3-thienyl) ethanol had been esterified firstly to avoid side reactions. After EDOT monomer and 2-(3-thienyl) ethyl acetate were mixed, both of them began to copolymerize. The copolymer of EDOT monomer and 2-(3-thienyl) ethanol had been obtained when the pre-product had been hydrolyzed and purified. The characterization of copolymer was measured and the related application was explored.

8811-39, Session 9

Performance improvement of polymer solar cells by ternary blending of amorphous and semi-crystalline polymer analogues with PCBM

Christian Kästner, Technische Univ. Ilmenau (Germany); Silke Rathgeber, Univ. Koblenz-Landau (Germany); Daniel A. M. Egbe, Johannes Kepler Univ. Linz (Austria); Harald Hoppe, Technische Univ. Ilmenau (Germany)

Ternary blending of amorphous and semi-crystalline anthracene-containing poly(p-phenylene-ethynylene)-alt-poly(p-phenylene-vinylene) (PPE-PPV) copolymers (AnE-PVs) with PCBM was investigated in bulk heterojunction solar cells. In general, a strong impact on all photovoltaic parameters was observed by increasing the amount of amorphous AnE-PVba-derivative in relation to its semi-crystalline counterpart AnE-PVab. Interestingly, small additions of the amorphous copolymer were beneficial for overall solar cell performance. The observed performance increase of the ternary blend could be related to an improved open-circuit voltage, despite the fact that the binary blend of the amorphous copolymer and [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) did not exhibit a larger photovoltage than the binary blend based on the semi-crystalline copolymer. These results indicate that a certain amorphous fraction of the donor polymer may be required for obtaining optimal bulk heterojunction morphologies, yielding maximum photovoltaic performance.

8811-43, Session 9

In-situ Raman spectroscopy, a new probe to monitor phase transformation and intercalation during spin-casting of bulk heterojunction solar cells

Maged Abdelsamie, Ahmed E. Mansour, Buyi Yan, Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia)

The microstructure and morphology of the bulk-heterojunction photoactive layer of organic solar cells plays a critical role in determining the photovoltaic performance. In certain types of polymer-fullerene blend systems, the fullerene can intercalate between the side chains of the donor polymer forming a mixed phase (solid state solution) in the place of or in addition to pure phases of the materials. Bimolecular crystals, also known as co-crystals, represent an ordered model system of the mixed phase in the bulk heterojunction layer, such as in case of PC71BM fullerene intercalation in the polymer poly(2,5-bis(3-hexadecylthiophen-2-yl)thieno[3,2-b]thiophene) (pBTTT-C16). The goal of this study was to investigate intercalation as it happens during spin-coating of the photoactive layer and to reveal its mechanism. Raman spectroscopy shows distinctive fingerprints for pure pBTTT and for the intercalated phase of pBTTT-PC71BM, including shifts in peak position and changes in relative peak intensities. In situ Raman spectroscopy was performed during spin-coating of pBTTT-PC71BM (1-1) in dichlorobenzene at 1000 rpms, showing a pure pBTTT phase present immediately from the beginning of the process, followed by intercalation of PC71BM into pBTTT near the end of the film formation process. The results suggest that PC71BM intercalation occurs after formation of the pure phase of pBTTT, rather than by crystallization of the intercalated phase from solution.

8811-32, Session 10

The challenges of modeling organic molecular materials *(Invited Paper)*

Clemence Corminboeuf, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

The performance of organic devices (e.g., charge-carrier mobility in field-effect transistors) depends heavily upon the organization and electronic structure of π-conjugated molecules or chains at the molecular level. To achieve the full potential of such materials, technological developments require fine-tuning of the specific intermolecular interactions spanning small ranges of distances, lateral displacements, and π-conjugated moiety orientations. The discovery pace of novel materials can be accelerated, considerably, by using efficient computational schemes where key characteristics are evaluated in silico. Our research focuses on the realization of efficient and accurate computational methods capable of simulating π-conjugated systems relevant to the field of organic electronics. The apparent simplicity of the chemical composition of π-conjugated systems contrasts the complexity of their electronic structure, where the most commonly used framework (i.e., density functional approximations) suffers from obvious failures. To achieve accurate predictions of organic molecular materials, we address lingering difficulties in describing charged radical oligomers (i.e., charge carrier), charge-transfer interactions, close π-stacking interactions, and near-degenerated electronic states.[1-3]

In addition to the quantum chemical aspects, focus is placed on mutliscale computational schemes capable of identifying key structure-property relationships in large assemblies of π-conjugated systems.

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8811-40, Session 10

The influence of sterics and molecular orientation on the open-circuit voltage in organic photovoltaics *(Invited Paper)*

Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Increasing the open-circuit voltage (VOC) in organic photovoltaics (OPVs) remains one of the key challenges to achieving higher power conversion efficiencies (PCEs); however, routes to achieving this increase are not well understood. In this presentation, we explore and discuss the roles of sterics and molecular conformation at the donor-acceptor interface in three model systems, namely (1) rubrene/C60 versus tetracene/C60, (2) ZnPc/C60 versus CuI/ZnPc/C60, as well as (3) PBDTTPD/C60 with systematically varying sidechains.

8811-41, Session 10

Organic photovoltaics at the nanoscale

Zeno Schumacher, Jessica Topple, Antoni Tekiel, Peter Grutter, McGill Univ. (Canada)

Nanoscale thin film morphology has been identified as an important factor in organic solar cell device functionality and efficiency. The understanding of loss mechanisms and structure-function relationships are key features on the way to more efficient organic solar cells.

However, it is difficult to study this effect in molecular solar cell devices. Therefore, one has to work on submonolayer molecular coverage and single molecule heterojunctions to study the behavior at the molecular length scale. We will present our latest achievements in fabricating and characterizing small molecule heterojunction on atomically flat alkali halide substrates in the nanoscale. We have reproducibly fabricated a Pentacene monolayer with lateral dimension of hundreds of nanometer. Furthermore, we grow Pentacene/3,4,9,10-perylenetetracarboxylic diimide (PTCDI) heterojunction in different orientations on the same sample. This enables us to study big ensembles of molecular interfaces under the exact same conditions. Additionally, each heterojunction can be observed individually due to the use of scanning probe microscopy.

Our system allows us to fabricate and characterize samples in ultra high vacuum, without exposing to air. To measure the structure-function relationship, a non-contact atomic force microscope (AFM) is used. Local electronic information is obtained by using Kelvin probe force microscopy (KPFM) while scanning the topography of the sample. Illuminating the sample with laser light during these measurements gives us further insight to the charge generation in organic solar cells.

This powerful combination of molecular heterojunction, AFM/KPFM measurements and laser illumination will help to better understand charge generation in organic photovoltaic.

8811-42, Session 10

Effects of the solvent additive dipole moment on bulk heterojunction solar cells based on low band-gap polymers

Olesia Synooka, Technische Univ. Ilmenau (Germany); Florian Kretschmer, Martin D. Hager, Friedrich-Schiller-Univ. Jena (Germany); Harald Hoppe, Technische Univ. Ilmenau (Germany)

The effect of the dipole moment of various solvent additives on the performance of photovoltaic devices, comprising of two different low band-gap polymers, namely benzothiadiazole-diketopyrrolopyrrole (BTD–DKPP) and poly[N-900-hepta-decanyl-2,7-carbazole-alt-5,5-(40,70-di-2-thienyl-20,10,30-benzothiadiazole (PCDTBT), combined with phenyl-butyric acid methyl ester (PCBM), has been investigated. In contrast to the common approach of using high boiling point solvent additives for control of fullerene aggregation after evaporation of the host solvent, we applied methanol and others in order to widely vary the molecular dipole moment. We found that the application of an additive concentration inversely proportional to the dipole moment yielded improvement of all solar cell parameters. The attribution of this effect is discussed on the basis of spectroscopic, electrical and morphological analysis.

8811-44, Session 11

Ultrafast IR-induced conductivity probing the dynamics of molecular systems *(Invited Paper)*

Artem A. Bakulin, FOM Institute for Atomic and Molecular Physics (Netherlands); Akshay Rao, Richard H. Friend, Univ. of Cambridge (United Kingdom); Huib J. Bakker, FOM Institute for Atomic and Molecular Physics (Netherlands)

Many organic and biological macromolecular systems like conjugated polymers, molecular crystals, photochromic proteins, or ionic membrane channels can be integrated into macroscopic electrical circuits using electrochemical cells or by developing an organic/protein monolayer diode structure [1]. In the latter case, the transmitted current can be used as a reporter for their structure and functionality, provided that the current flux is coupled to the local electronic or/and vibrational modes. This concept enables the study and control of the structure, dynamics, and conductivity of macromolecular systems by measuring changes in electric current that result from an optical excitation ('push') with IR light.

To study the coupling between conductivity and optical IR excitation we have developed an IR-push -- photocurrent probe technique [2]. We applied this technique to a wide range of molecular systems, including plastic photovoltaic cells and organic monolayer based diodes. For photovoltaic cells [2,3] the excitation with IR light leads to the promotion of charges to delocalised states. Although such states are extremely short-lived (<1ps), their excitation enables the charges to overcome the Coulomb attractive interaction and to become separated.

We also observe a strong change of the conductivity after excitation with IR light in the spectral region of C-C vibrational modes at ~1400-1600 cm-1. The physical phenomena underlying this effect are currently under investigation.

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8811-45, Session 11

Efficient free charge carrier generation from charge-transfer states in organic solar cells *(Invited Paper)*

Koen Vandewal, Stanford Univ. (United States)

Efficient organic solar cells combine a high yield of photo-induced free charge carriers with a minimum of amount of energy lost in the electron transfer process from electron donor (D) to electron acceptor (A) materials. Decay of the photo-excitations at the D-A interface via interfacial charge transfer (CT) states can result in quantum yields of free charge carrier generation less than unity. Here we investigate the role of the lowest energy, relaxed charge transfer state (CT0) in the free charge carrier generation process by comparing the quantum yields of charge generation obtained from selective excitation of CT0 to that from the higher energy excited states. We use the electroluminescence spectra (EL) of solar cell devices to identify the lowest energy emissive excited state, (CT0), and develop a method to measure the photon energy dependence of the quantum yield of free carrier generation when exciting these low energy states. Additionally, we use a time delayed collection field technique with variable excitation wavelength to compare the electric field dependence of the charge generation process for above polymer gap excitations with direct CT state excitation. For a series of polymer:fullerene, small molecule:C60 and polymer:polymer photovoltaic devices, we find that the field dependence and absolute quantum yield for free carrier generation is essentially independent of whether or not states with higher energy than CT0 are excited. This result indicates that excess energy is not needed to obtain a high yield of free charge carriers from CT states at D-A interfaces.

8811-46, Session 11

Neighbor effect in charge-transfer complex formation in conjugated polymer: acceptor blends

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Weak intermolecular charge-transfer complex (CTC) in the electronic ground state can be formed between a conjugated polymer and low-molecular-weight acceptor. The CTCs can influence the photophysics, polymer conformation and blend morphology. Formation of conjugated polymer CTCs is a much more complex process compared to that in low-molecular-weight blends [1]. Specifically, in solution of the MEH-PPV:(2,4,7-trinitrofluorenone) (TNF) blend, CTC concentration CCTC shows a threshold increase with the acceptor content Ca, in contrast to a gradual increase typically observed in low-molecular-weight blends. The threshold-like behavior was assigned to the neighbor effect: new CTCs are preferentially formed near the existing ones [1].

In this work, we show that the recently proposed analytical neighbour effect model [2] describes absorption, thermochromic, and PL quenching data of conjugated polymer:acceptor blends' solutions. Firstly, we present absorption data for different blends and show that the model explains CCTC(Ca) dependences obtained from them. We discuss how the neighbor effect depends on the acceptor molecular skeleton, substituents, electron affinity, donor concentration and solvent. Secondly, we show that the model [2] describes qualitatively main features of the CCTC dependence on temperature: a threshold-like curve shape and hysteresis in cooling and heating. Thirdly, we present an analytical model of photoluminescence (PL) quenching by acceptor. This model explains the observed moderate quenching that implies formation of CTC aggregates [3].

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8811-47, Session 11

The influence of the donor-acceptor interface on charge-transfer state energies and the open-circuit voltage in organic photovoltaics

Kenneth R. Graham, King Abdullah Univ. of Science and Technology (Saudi Arabia) and Stanford Univ. (United States); Patrick Erwin, The Univ. of Southern California (United States); Dennis Nordlund, Stanford Synchrotron Radiation Lightsource (United States); Koen Vandewal, Stanford Univ. (United States); Ruipeng Li, Guy O. Ngongang Ndjawa, King Abdullah Univ. of Science and Technology (Saudi Arabia); Eric T. Hoke, Alberto Salleo, Stanford Univ. (United States); Mark E. Thompson, The Univ. of Southern California (United States); Michael D. McGehee, Stanford Univ. (United States); Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia)

The power conversion efficiencies (PCEs) of organic photovoltaics (OPVs) currently suffer from relatively large energetic losses between the optical gaps of the absorbing materials and the open-circuit voltage (VOC). If these energetic losses could be decreased, the V¬OC, and thus the PCE, could be increased. Previously it has been proposed that the VOC can be increased by decreasing the electronic coupling between donor and acceptor molecules, with support for this claim coming from current-voltage modeling utilizing forms of the ideal diode equation. In our work, tetracene/C60 and rubrene/C60 bilayer systems were analyzed and the electronic coupling parameters measured directly from sub-bandgap external quantum efficiency measurements. Analysis of these systems reveals that the VOC differences correspond directly with the differences in the charge transfer state energies (ECT), with little to no influence from electronic coupling. Furthermore, based on near-edge X-ray absorbance fine structure spectroscopy and grazing incidence X-ray scattering measurements to probe molecular orientation, the electronic coupling differences can be ascribed to the edge-on and more face-on orientations adopted by tetracene and rubrene respectively. To address the question of what determines ECT, we probe the HOMO levels and ECT of both crystalline and amorphous systems, with results showing that ECT is influenced both by HOMO-LUMO levels and the degree of crystallinity.

8811-48, Session 11

Ultrafast hot exciton dissociation at organic interfaces *(Invited Paper)*

Giulia Grancini, Daniele Fazzi, Istituto Italiano di Tecnologia (Italy); Margherita Maiuri, Politecnico di Milano (Italy); Annamaria Petrozza, Istituto Italiano di Tecnologia (Italy); Daniele Brida, Univ. Konstanz (Germany); Giulio Cerullo, Politecnico di Milano (Italy); Guglielmo Lanzani, Istituto Italiano di Tecnologia (Italy)

Interface physics is at the heart of photovoltaics (OPV). Common knowledge suggests that at the interface photons get absorbed and charge separation takes place within 100fs. However, the actual charge generation mechanism on such a short timescale is still hot debated.

Here, we monitor for the first time, thanks to sub-15-fs pump-probe spectroscopy, the exciton dissociation pathways in a low-band gap polymer: fullerene (PCPDTBT:PCBM) blend.

We find that exciton dissociation leads to both bounded interfacial CTS and free polarons within a time scale of 20-50fs, with a branching ratio that depends on the excess energy. In particular, upon band-gap excitation, the resonant lower-energy CT1 state and polarons are populated. However, in the first 500fs, the CT1 does not evolve, indicating that it does not contribute to the early-time charge dissociation yield. On the other hand, by above-gap excitation, a fast conversion to the hot CTS* manifold happens (t=22fs). Such hot CTS* are more delocalized in nature, thus more prone to further separate into polarons (t=150 fs), before thermalization to CT1. Thanks to stronger coupling between high-energy-states and hot CTS*, we demonstrate the opening of additional paths for charge generation that would otherwise be quenched by internal conversion to the lowest-lying states. Providing a large excess energy amount, the higher-lying polymer singlet states dissociate before internal conversion, ultimately leading to a higher fraction of polarons. Our results provide a new framework to understand charge generation in OPV system, suggesting that hot dissociation is a strategic option to enhance the photovoltaic conversion.

8811-49, Session 12

Ultrafast dynamics of photogeneration and motion of excitons and charges in conjugated polymers and blends for photovoltaics *(Invited Paper)*

Laurens D. A. Siebbeles, Technische Univ. Delft (Netherlands)

We studied the nature and dynamics of photoexcited states in blends of the polymer poly(3-hexyl-thiophene) (P3HT) and the electron acceptor PCBM by ultrafast optical and terahertz spectroscopy. The relative initial yield of free charges and excitons increases with photon energy. The yield of charges produced promptly upon photoexcitation is independent of temperature. This is attributed to charge delocalization causing the electron-hole Coulomb attraction to be negligible.[1,2]

The near IR part of the solar spectrum can be harvested by adding PbS quantum dots to yield ternary P3HT:PCBM:PbS blends. Using ultrafast optical spectroscopy, we found that photoexcitation of PbS quantum dots leads to hole transfer to P3HT and electron transfer to PCBM.3 However, we found from terahertz photoconductivity measurements that the excess charges in the organic components are immobile. This is explained by Coulomb interaction with charges or induced dipoles on the quantum dots.

The spatial delocalization and diffusion of excitons along MDMO-PPV chains was studied with ultrafast optical spectroscopy and density functional theory. We infer that photoexcitation leads to excitons that are initially largely delocalized along a polymer chain over ~ 100 monomers. Annihilation of two excitons produced within this distance on the same polymer chain decay within a few hundred femtoseconds. Interchain exciton diffusion and second order exciton-exciton annihilation occurs on longer times.

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8811-50, Session 12

Optical probes of charge generation and recombination in low-bandgap polymer: fullerene organic solar cells *(Invited Paper)*

Frédéric Laquai, Max-Planck-Institut für Polymerforschung (Germany)

I will discuss the photophysics of state of the art bulk heterojunction thin films using different low-bandgap polymers as electron donors. By using a broadband probe and near-infrared detection scheme we are able to monitor the hitherto unobserved near-infrared spectral probe region between 1000-2000 nm. This allows us to identify the individual spectral contributions and dynamics of singlet and triplet excitons, charge-transfer (CT) states as well as free and mobile charge carriers in low-bandgap polymer:fullerene blends. We observe that in addition to ultrafast (<100 fs) charge generation a common feature of these blends is delayed charge generation caused by diffusion-limited exciton dissociation mainly occurring from PCBM-rich domains of the photoactive layer. Furthermore, a generic feature of these blends appears to be nanosecond geminate recombination of interfacial CT-states causing a reduction of the short circuit current. We find that in efficient photovoltaic blends the extraction of free charges is mainly competing with non-geminate charge recombination thereby determining the device fill factor, while field-dependent charge generation processes only play a minor role. By modeling our experimental data we can extract the fraction and formation rate of CT-states and free charges, the recombination rate of interfacial CT-states and the non-geminate recombination coefficient as well as the order of the non-geminate recombination process. Additionally, by using a novel time-delayed double pump technique we can determine the charge carrier mobility, get insights into the bias dependence of non-geminate recombination and validate the non-geminate recombination coefficients obtained by TA spectroscopy.

8811-51, Session 12

Coherence, uncertainty, and opportunity for organic photovoltaics

Loren G. Kaake, Alan J. Heeger, Univ. of California, Santa Barbara (United States)

Transient absorption measurements were performed on organic bulk heterojunction films comprised of different materials and employing different donor-acceptor ratios. The hole generation dynamics were measured by integrating a region of photoinduced absorption. The spectral assignments were in accord with previous literature reports, and coincided with our observation of long lived photoinduced absorption signals which represent the signature of shallowly trapped charge carriers. The charge generation dynamics show an ultrafast charge generation component and a component of charge generation which follows exciton diffusion. Surprisingly, the number of carriers generated on ultrafast timescales and the number of carriers produced following exciton diffusion show a ratio which is independent of the constituents of the bulk heterojunction. This indicates that simplistic models of exciton diffusion fail at ultrafast timescales. The effect is explained by stating that coherence provides for a spatially delocalized initial photoexcited wavefunction . This interpretation is further supported by similar measurements on a simpler donor-acceptor bilayer.

8811-52, Session 13

Multi-THz spectroscopy of mobile charge carriers in P3HT:PCBM on a sub-100 fs time scale *(Invited Paper)*

David G. Cooke, McGill Univ. (Canada); Frederik C. Krebs, Peter U. Jepsen, Technical Univ. of Denmark (Denmark)

The dynamics of mobile charge carrier generation in polymer bulk heterojunction films is of vital importance to the development of more efficient organic photovoltaics based on conjugated polymers. As with conventional semiconductors, the optical signatures of mobile carriers lies in the far-infrared (1 – 30 THz) although the electrodynamics deviate strongly from Drude. The key time scales for the process are picoseconds to sub-100 fs, and therefore becomes a challenge to perform low energy spectroscopy on these time scales as it is less than the period of oscillation for the probing light.

In this work, we demonstrate sub-100 fs spectroscopy of a polymer bulk heterojunction film P3HT:PCBM using a single-cycle, phase-locked and coherently detected multi-THz transient as a probe pulse following femtosecond excitation at 400 nm. By observing changes to the reflected THz transients from the film surface following photoexcitation, we can extract the complex optical conductivity spectrum for the film in snapshots of 40 fs following photoexcitation. We find that for our excitation conditions, mobile charges are created in less than 120 fs and are characterized by a spectrum which is consistent with that of a two-dimensional delocalized polaron. Approximately 2/3 of these initially mobile carriers relax to a localized state on a 1 ps time scale while the remainder remain mobile over much longer time scales. We conjecture that the fast decay is a signature of the re-formation of the exciton and therefore a major loss channel for polymer photovoltaics.

8811-53, Session 13

The driving force for electron transfer in conjugated polymers and blends with novel fullerenes *(Invited Paper)*

Garry Rumbles, National Renewable Energy Lab. (United States)

The driving force for electron transfer between a donor conjugated polymer and a fullerene acceptor is often given as the LUMO offset between the two species. While this is a reasonable approximation, it does not correctly include the exciton binding energy associated with the excited state, or exciton. This presentation will examine the role that the electron affinity of the acceptor plays in controlling the photo-induced electron transfer process of an excited state resident on either the conjugated polymer or the fullerene. Using the technique of flash photolysis, time-resolved microwave conductivity (fp-TRMC) the process of generating separated, or uncorrelated electron-hole pairs, will be discussed.

The presentation will examine charge carrier generation in blends of conjugated polymers with a number of perfluroalkyl-substituted fullerenes, with substitution motifs that control both the steric hinderance around the fullerene, as well as the electron affinity. In addition to the driving force for the electron transfer, the impact that the substitution pattern has on the microwave electron mobility will also be discussed.

8811-55, Session 13

When is hot CT state dissociation important in organic photovoltaics?

John B. Asbury, The Pennsylvania State Univ. (United States)

The dynamics of charge separation in photovoltaic polymer blends following photoinduced electron transfer from the conjugated polymer, regioregular-P3HT, to electron acceptors are observed with ultrafast vibrational spectroscopy. The investigators take advantage of a solvatochromic shift of the vibrational frequency of the carbonyl (C=O) stretch of the acceptors to directly measure the rate of charge transfer state dissociation to form charge separated states. Two acceptor classes are examined – functionalized fullerenes (PCBM) and perylene diimides (PDIs). Charge separation in rr-P3HT:PCBM blends occurs through activationless pathways and occurs on the sub-nanosecond time scale – too slow for hot CT state dissociation to be important. In contrast, rr-P3HT:PDI blends exhibit activated charge separation on the picosecond time scale where hot CT state dissociation may influence the yield of separated electrons and holes. The variation in charge separation mechanism arises from differences in the degree of electron delocalization that the electron acceptors can support.

8811-59, Session 13

The nature of long-lived charges in co-crystallized and phase-segregated polymer: fullerene blends

Fei Dou, Ecole Polytechnique de Montréal (Canada) and Univ. de Montréal (Canada); Ester Buchaca-Dormingo, Imperial College London (United Kingdom); Maciej Sakowicz, Univ. de Montréal (Canada); Xinping Zhang, Beijing Univ. of Technology (China); Natalie Stingelin-Stutzmann, Imperial College London (United Kingdom); Carlos Silva, Univ. de Montréal (Canada)

The optoelectronic properties of donor-acceptor conjugated polymer blends are highly dependent on film solid-state microstructure, which can be fantastically complicated. In particular, in semicrystalline polymer:fullerene blends, several combinations of morphologies are possible between the two components (i.e. crystalline/crystalline, crystalline/amorphous, etc.). Deep understanding of how these contrasting morphologies affect optoelectronic processes, like charge generation and recombination processes, is a fundamental issue in plastic electronics in order to optimize material design and exploiting them in efficient organic semiconductor devices. In this work, we focus on two contrasting microstructures: co-crystallized and phase-segregated poly(2,5-bis(3-tetradecyllthiophen-2-yl)thieno[3,2,-b]thiophene)(pBTTT):phenyl-C61-butyric acid methyl ester (PC60BM) blends, achieved by use of additives that exclude PCBM from the pBTTT crystal, to study the nature of long-lived charges by quasi-steady state photoinduced absorption (PIA) spectroscopy. We find that triplet-excitons and polarons are generated in both microstructures. However, polarons in the co-crystallized film are more highly localized than in phase-separated microstructures. By means of the quasi-steady-state solution of a mesoscopic rate model, we demonstrate that the polaron generation efficiency is higher than the triplet-exciton generation efficiency in these two blends, and that both the polaron generation efficiency and recombination rates are higher in the co-crystallized blend than in the phase-separated blend.

8811-56, Session 14

Dual channel photocurrent harvesting in organic solar cells *(Invited Paper)*

Paul Meredith, Paul L. Burn, Ajay K. Pandey, Yuan Fang, Chen Tao, The Univ. of Queensland (Australia); Nikos Kopidakis, Alex Nardes, National Renewable Energy Lab. (United States)

Organic solar cells contain two essential components in the active junction region: a high electron affinity electron acceptor and a lower electron affinity electron donor. The interface between these two components provides the driving force to separate the Coulombically bound photoexcitation (exciton) into free carriers for extraction to the external circuit (i.e. the generation of photocurrent). In conventional organic solar cells, the electron donor has predominantly provided the photon absorbing function and photocurrent is generated by the so-called Channel I pathway of photo-induced electron transfer (PET). These interfacial dynamics are complex and thought to be mediated via charge transfer (CT) states. However, more recently, it has been proposed and demonstrated that the so-called Channel II process can be an equally efficient current generating pathway whereby photon absorption occurs in the electron acceptor followed by photo-induced hole transfer (PHT) [1]. In principle, with the appropriate design of acceptor and donor, both Channels can operate simultaneously and one can realise the concept of "complementary absorbers" in a single junction organic solar cell. In my talk I will discuss our recent efforts to both demonstrate the utility of the Channel II process and design complementary acceptor-donor pairs. I will discuss the individual elements of both current generating pathways using Channel I and Channel II state diagrams, and furthermore estimate the contributions to photocurrent from each channel. The concept of complementary acceptor-donor pairs is another tool that we can use to further improve the overall efficiency of organic solar cells.

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8811-57, Session 14

What controls exciton dissociation in polymeric donor-acceptor solar cells? *(Invited Paper)*

Anna Kohler, Univ. Bayreuth (Germany)

Efficient exciton dissociation at a donor-acceptor interface is a necessary condition for obtaining high efficiency polymeric solar cells. Despite its importance, this step is still not fully understood. A central question is how and why, after photoexcitation of the donor and transfer of an electron onto the acceptor, the the e-h pair can overcome their considerable mutual Coulomb potential. Possibilities that are currently discussed include the role of the excess energy, liberated when the excited donor electron transfers to the acceptor, the degree of delocalization of both an exciton and a charge in a conjugated polymer, interfacial dipoles that may exist at the donor-acceptor interface in the ground state, and the degree of energetic and structural order/disorder. In this talk I will show how we combine insight gained from ultrafast pump-probe spectroscopy, field dependent photocurrent measurements, photoemission measurements and modeling to assess which factors control the dissociation process.

Related publications:

D. Herrmann et al., J. Am. Chem. Soc. 133 (2011) 18220-18233

Role of Structural Order and Excess Energy on Ultrafast Free Charge Generation in Hybrid Polythiophene/Si Photvoltaics Probed in Real Time by Near-Infrared Broadband Transient Absorption

C. Schwarz et al. , Adv. Mater. 24 (2012) 922–925

Does conjugation help exciton dissociation? A study on poly(p-phenylene)s in planar heterojunctions with C60 or TNF

C. Schwarz et al., submitted

On the Role of the Effective Mass and Interfacial Dipoles on Exciton Dissociation in Organic Donor-Acceptor Solar Cells

8811-58, Session 14

Exciton diffusion and charge separation in conjugated polymers and fullerenes *(Invited Paper)*

Ifor D. W. Samuel, Alexander J. Ward, Zarifi Masri, Arvydas Ruseckas, Univ. of St. Andrews (United Kingdom)

The generation of charge in organic semiconductors requires the diffusion of excitons to an acceptor. We present a detailed study of this process including separating contributions from direct energy transfer and diffusion to an interface. We compare and contrast a range of methods for measuring exciton diffusion notably surface quenching, exciton-exciton annihilation and volume quenching. In all cases time-resolved fluorescence measurements are used to learn about this important process and relate it to polymer solar cell materials and devices.

8811-60, Session PWed

Electrocatalytic bulk heterojunction materials

Matthew P. Gustafson, Monash Univ. (Australia)

This project has synthesised and characterised poly(thieno[3,2-b]thiophene) (PTT) and poly(dithieno[3,2-b:2',3'-d]thiophene) (PDTT) via vapour phase polymerisation (VPP). These conducting polymers (CPs) possess adequate light absorption in the UV-visible range to promote solar excitation making them ideal candidates to help form a light-enhanced 3D bulk heterojunction material.

Furthermore, their unique structure allows for slight alterations in configuration to provide alternate band gaps in an attempt to 'tune' the material to the operational window specific to a particular reaction. Once characterisation was complete, PTT was combined successfully with poly(3,4-ethylenedioxythiophene) (PEDOT) forming a composite mixture. Preliminary testing indicates the two CPs have a certain level of spontaneous interaction. The trend is seen in the absorption spectra where the increased ratio of PTT leads to the n-n* transition shifting towards the PTT spectrum while retaining the characteristic PEDOT 'tail'. This was the first indication that the combination of CPs via VPP had been successful and that both characteristics typical of each polymer could be sustained. It is important to note that VPP is convenient for this application as it allows one film to be polymerised into another. This could not be achieved through chemical means as a co-polymer may be produced.

It then follows that a combination of these polymers will result in significant advantages owing to their complimentary properties; PTT/PDTT increasing light absorption while PEDOT providing a junction to aid in charge separation and avoiding recombination. Thus, a beneficial blend can be produced and the 3D junction optimised.

8811-61, Session PWed

Passivated aluminum: structure and energy level alignment at surfaces and interfaces

Eung-Gun Kim, Dankook Univ. (Korea, Republic of); Jean-Luc Bredas, Georgia Institute of Technology (United States)

We present a structural model for the Al2O3(0001)/Al(111) interface based on DFT calculations. By removing a sub-nm, finite-size effect that made a more stable structure less accessible in the smaller surface unit cells commonly used in theoretical calculations, we have been able to determine a new model for the interface. Unlike the structure previously proposed, our calculations underline that the interface consists of a metal-like layer and an oxide-like layer, which now makes the structural transition across the ultrathin interface gradual. Calculations based on the new interface structure successfully reproduce the experimental barrier height of 3.2 eV, and predict a work function reduction of 0.49 eV in passing through the oxide at both the interface and the surface. We expect that this new interface model will serve as a useful platform to further explore this fundamentally and technologically important interface in such emerging areas as organic electronics, where the passivated Al metal, in combination with SAMs, finds applications as high-performance cathode and gate materials.

8811-62, Session PWed

Plasmonic enhanced lasers of nano-colloidal fluids

Pascal André, Univ. of St. Andrews (United Kingdom) and RIKEN (Japan); Neda Ghofraniha, Istituto Nazionale di Fisica Nucleare (Italy) and Univ. degli Studi di Roma La Sapienza (Italy); Andrea Di Falco, Univ. of St. Andrews (United Kingdom); Claudio Conti, Univ. degli Studi di Roma La Sapienza (Italy)

Localized surface plasmon resonances have recently attracted considerable attention due to their ability to dramatically enhance near-field optical intensities and boost nanoscale light-matter interactions. Here we demonstrate unambiguously that polyhedral silver nanoparticles can be tailored to promote enhanced coherent emission from organic dye dispersions in a cavity. In particular, we observe that nanoparticles supporting resonances close to the absorption peak of the dye yield to more efficient lasing, up to one order of magnitude, which is also evidenced by the narrowing of the emission spectral line down to 3 nm. Moreover we observe emission saturation and energy dependent spectral shifts associated with Kerr effects, which demonstrates the general relevance of non-resonant nonlinearities in plasmonic enhanced laser emissions. Works in this area will contribute to the design of novel kind of laser sources providing ultra-short pulsed operation and structural tunability.

8811-63, Session PWed

Preparation and characterization of cobalt ferrite nanoparticles for immobilization

Priscyla L. Andrade, Valdeene A. J. Silva, Jackeline Maciel, Univ. Federal de Pernambuco (Brazil); Nelson O. Moreno, Univ. Federal de Sergipe (Brazil); Luis Valladares, Univ. of Cambridge (United Kingdom); Angel B. Dominguez, Univ. Nacional Mayor de San Marcos (Peru); Maria da Paz Silva, José Albino Aguiar, Univ. Federal de Pernambuco (Brazil)

Cobalt ferrite has attracted considerable attention in recent years due to its unique physical properties such as high Curie temperature, large magnetocrystalline anisotropy, large magnetostrictive coefficient, excellent chemical stability and mechanical hardness [1]. On the other hand, enzymes immobilization is considered to be an important tool to enhance thermal and operational stability, easy separation from the reaction mixture during down streaming and reusability for industrial applications [2]. An important requirement for protein immobilization is that the matrix should provide a biocompatible and inert environment, i.e. it should not interfere with native structure of the protein, which thereby could compromise its biological activity [3]. The purpose of this work was to study preparation and functionalization of cobalt ferrite nanoparticles and their application as solid supports for enzymes immobilization. Magnetic particles were prepared in the presence of oleic acid. Aqueous suspension of magnetic particles were prepared by coprecipitation of Fe(III) and Co(II) in the presence of NaOH. The samples were characterized by X-ray diffraction, electron scanning microscopy (SEM), FTIR spectroscopy, mossbauer spectroscopy and magnetization

measurements. Our results indicate that oleic acid produces changes in the size and morphology of the cobalt ferrite nanoparticles and in the magnetization properties. These magnetic nanoparticles were tested as matrix for enzyme immobilization. The immobilized trypsin enzyme in cobalt ferrite with oleic acid presented a specific activity of 38% after 10 reuses.

8811-64, Session PWed

Insulating conduction in amorphous silicon-chromium films

Abdelhamid El Kaaouachi, Mohamed Errai, Abdelfattah Narjis, Said Dlimi, Abdelghani Sybous Jr., Lhoussine Limouny, Univ. Ibn Zohr (Morocco); Hassan El idrissi, Hassan II Univ. (Morocco)

In this work we focus on the problem of the low temperature transport in insulating amorphous Si1-xCrx films (x=10.9, 12.7 and 14.9%). The conductivity is best described by the relation σ=σ0exp[-(T0/T)p] with p≈1/4. This behavior can be explained by Mott Variable Range Hopping model where the transport occurs by hopping between localized states in the vicinity of the Fermi level without creation of the Coulomb Gap. This is found to be true for the three alloys, but the temperature range where this model is valid decreases with increasing chromium fraction

8811-65, Session PWed

Probing the Coulomb gap in 2D Si-MOSFETs

Abdelhamid El Kaaouachi, Lhoussine Limouny, Abdelfattah Narjis, Abdelghani Sybous Jr., Said Dlimi, Univ. Ibn Zohr (Morocco); Hassan El Idrissi, Hassan II Univ. (Morocco); Gerard Biskupski, Univ. des Sciences et Technologies de Lille (France)

We investigate the temperature dependence of the electrical resistivity down to 0.2 K of a two dimensional electron system in n-channel Si-MOSFETs at zero magnetic field, and at low electron densities, near the metal-insulator transition point from the insulating side. Our results show the existence of a crossover from Mott regime at very low temperature, where ρ= ρ0 exp(TM /T)1/3 to Efros-Shklovskii variable range hopping (ES-VRH), witch is consistent with the existence of a Coulomb gap, where ρ= ρ0 exp(TES /T)1/2. With ρ0 is a Pre-exponential factor that is found to be close to 2 (h/e2), this crossover occurs when the value of temperature oscillates around 1 K.

8811-66, Session PWed

Generation of spin-polarized atomic clusters: high-precision calculations with modified SV5LYP method

Xuan Liu, Haruhiko Ito, Tokyo Institute of Technology (Japan)

The spin clusters made up of a small number of alkali-metal atoms are stable in the lowest spin state and become unstable as the total spin of the system increases. The calculation value is in good agreement with the experimental data in the lowest spin state. On the other hand, the former differs by more than 80 % from the latter in the highest spin state, although there are only a few experimental results on dimers and trimers. To show the possibility of the formation of the spin clusters in the highest spin state, we perform computations of the binding energy of the spin clusters, Rbn and Csn with n=2 to 14, using the density functional method as precise as possible. Indeed, by changing the parameter values of both the local exchange energy and the non-local correlation energy appearing in the SV5LYP method, the difference from the experimental data is reduced to less than 1 % in both cases of dimers and trimers in the highest spin state. The cluster geometry changes with the total spin. The tetramers are parallelogram in the lowest spin state and tetrahedral in the highest spin state. Such variation between planar structures and steric structures is caused by the change of the exchange energy. When the dihedral angle is 70.53 degree, namely the regular tetrahedron, the exchange energy of the tetramers in the highest spin state reaches a peak.

8811-67, Session PWed

Improved device performance of TIPS-pentacene field effect transistors incoporating solvent additives

Giljo Chae, Seunghyon Jung, Jeonghoon Baek, Dong-A Univ. (Korea, Republic of); Bright J. Walker, Ulsan National Institute of Science and Technology (Korea, Republic of); Chungkun Song, Jung Hwa Seo, Dong-A Univ. (Korea, Republic of)

Improved device performance of 6,13-bis(triisopropylsilylethynyl) pentacene (TIPS-pentacene) field effect transistors (FETs) was achieved via solvent additives, where diphenly ether (DPE) and chloronaphthalene (CN) were used. The hole mobilities increased from 0.2 cm2V-1s-1 for the pristine device to 0.75 cm2V-1s-1, when TIPS-pentacene FETs processed with DPE and CN were optimized at annealing temperature of 46°C and 60°C, respectively. The concentration of both DPE and CN critically affects the device performance. To understand the effect of additives on surface morphology, molecular ordering and crystallinity of TIPS-pentacene, scanning electron microscopy (SEM), X-ray diffraction (XRD) and optical microscopy measurements were carried out. Appropriate amount of additive induced the formation of well-ordered crystalline domains in TIPS-pentacene, leading to efficient hole transport. Additionally, reduced contact resistance were observed in devices processed with additives compared to neat TIPS-pentacene FET devices. Our findings suggest therefore that the use of additives constitutes a new and effective methodology for the fabrication of OFETs with improved performance

8811-68, Session PWed

Characterization of fucan and oleic acid-fucan coated magnetite nanoparticles for Sarcoma-180 treatment

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In recent years, there has been a growing interest in the development of Fe3O4 -based nanoparticles as prospective candidates for the diagnosis and targeted therapy of cancer [1]. The optimization and functionalization of these magnetic nanoparticles are very promising for vast applicability. They are usually presented in core-shell configurations: a magnetic nucleus coated with organic or polymeric shells [2]. Fucans are sulfated polysaccharides that possess many biological activities such as anticoagulant, antiviral, antitumoral, anti-inflammatory, and thus good candidates for the functionalization of Fe3O4 nanoparticles [3]. On the other hand, oleic acid is often used as a surfactant and has higher affinity to the surface of superfine magnetite [4]. The objective of this work was to synthesize fucan and fucan-oleic acid coated magnetite nanoparticles by co-precipitation methods, to characterize and to analyze any modification on nanoparticles' surface, and to test them for antitumoral activity. The samples were characterized by scanning electron microscopy (SEM), infrared spectroscopy (FTIR), x-ray diffraction (XRD), magnetization measurements and Mössbauer spectroscopy. The SEM showed that the nanoparticles (around 10 nm size) present heterogeneous morphology. The coating efficiency of fucan and oleic acid on the surface of the magnetite nanoparticles was analyzed by FTIR.

The functionalization of the Fe_3O_4 nanoparticles is demonstrated by FTIR and XRD The magnetization curves indicate typical superparamagnetic behavior for all the samples and this property is originated by the core Fe_3O_4 . The uncoated and coated magnetite nanoparticles were applied for antitumoral activity in mice with Sarcoma 180.

8811-69, Session PWed

Positive magnetoresistance and spin susceptibility in two-dimensional electron gas in GaAs

Hassan El Idrissi, Hassan II Univ. (Morocco); Abdelhamid El Kaaouachi, Abdelfattah Narjis, Said Dlimi, El Fatmi Daoudi, Abdelghani Sybous Jr., Mohamed Errai, Lhoussine Limouny, Univ. Ibn Zohr (Morocco)

In this work, positive magnetoresistance (PMR) of a dilute two-dimensional electron gas in GaAs is studied at very low temperature in presence of parallel magnetic fields B on the metallic side far away from the metal insulator transition (MIT). It turns out that the normalized resistivity curves, $\chi(B)/\chi(0)$, merge together when we scale the field according to B/B_χ where B_χ is assumed to be the field in which full spin polarization of electrons is reached. It is also shown that the saturation field, Bsat, determined by resistivity saturation, deviates to lower values than B_χ with increasing electron density, which cannot be explained in terms of filling of the upper electron subbands in the fully spin-polarized regime. The spin susceptibility, χ, is assessed by extracting the product g^*m^* where g^* and m^* are the effective Landé factor and electron mass, respectively. The behaviour of χ with increasing electron density is still the subject of required theoretical attention.

8811-70, Session PWed

Granular and intergranular conduction in granular oxides La0.67Ca0.33MnO3 and La0.5Sr0.5CoO3

Abdelhamid El Kaaouachi, Abdelfattah Narjis, Lhoussine Limouny, Said Dlimi, Abdelghani Sybous Jr., El Fatmi Daoudi, Mohamed Errai, Univ. Ibn Zohr (Morocco); Hassan El Idrissi, Hassan II Univ. (Morocco)

Electrical transport is studied in nanocrystals of $La_{0.67}Sr_{0.33}MnO_3$ (LCMO) and $La_{0.5}Sr_{0.5}CoO_3$ (LSCO) in the temperature range 0.4-5 K. In both samples, two distinct behaviors of the conductivity are observed. In LCMO sample, the Variable Range Hopping regime is observed for T>1 K with enhancement of the relative permittivity. On contrary, for LSCO sample, there is no latitude at all that could allow the possibility of this model being valid. For T<1 K, the transport model in both samples is considered in the two component model of metallic-like droplets embedded in dielectric matrix where the negative magnetoresistance can be explained by considering the Spin Polarization Tunneling phenomenon in the intergranular regions.

8811-71, Session PWed

Observation of screening-induced metallic behavior in n-AlAs

Abdelhamid El Kaaouachi, Abdelfattah Narjis, Said Dlimi, Mohamed Errai, Abdelghani Sybous Jr., El Fatmi Daoudi, Univ. Ibn Zohr (Morocco)

The nature of the metal-insulator transition at zero magnetic field in two-dimensional systems has remained a controversial enigma since the pioneering realization of the metallic behaviour in high mobility Si-MOSFETs. In this paper the density (n) dependence of the conductivity of two-dimensional electron gas in aluminum arsenide was analyzed in the metallic side ($n \geq 0.59?1011cm-2$) at very low temperature. Our study reveals an inhomogeneity driven percolation type transition to an insulating state due to the breakdown of screening in the random charged impurities disorder background. The critical density found under this assumption is lower than that assumed by observing the sign of the temperature coefficient of conductivity.

8811-72, Session PWed

Spin polarization in two-dimensional hole gas in GaAs

Abdelhamid El Kaaouachi, Said Dlimi, Abdelghani Sybous, Lhoussine Limouny, Abdelfattah Narjis, Univ. Ibn Zohr (Morocco); Gerard Biskupski, Univ. des Sciences et Technologies de Lille (France); Mohamed Errai, Univ. Ibn Zohr (Morocco); Hassan El Idrissi, Hassan II Univ. (Morocco); El Fatmi Daoudi, Univ. Ibn Zohr (Morocco)

In the ballistic regime where $kBT\tau 0/ \hbar > = 1$, the temperature dependence of the metallic conductivity in a two-dimensional holes system in gallium arsenide, is found to change in a non-monotonically with the degree of spin polarization. In particular, its fades away just before the onset of complete spin polarization, but reappears again in the fully spin-polarized state, being, however, suppressed relative to the zero magnetic field case. The analysis of the degree of suppression can distinguish between screening and theories based on interaction. We show that in a fully polarized spin state, the effects of disorder are dominant approach to strong localization regime, which is contrary to the behavior of 2D electron systems in weakly unpolarized disordered state. It was found that the relaxation time correction elastic, depending on the temperature has changed significantly with the degree of spin polarization, to reach a minimum just below the start of the spin-polarized integer, where the conductivity is practically independent temperature.

8812-1, Session 1

Ionic contrast terahertz near field imaging *(Invited Paper)*

Guilhem Gallot, Ecole Polytechnique (France)

We demonstrated the direct and noninvasive imaging of functional neurons by Ionic Contrast Terahertz (ICT) near-field microscopy. This technique provides quantitative measurements of ionic concentrations in both the intracellular and extracellular compartments and opens the way to direct noninvasive imaging of neurons during electrical, toxin, or thermal stresses. Furthermore, neuronal activity results from both a precise control of transient variations in ionic conductances and a much less studied water exchange between the extracellular matrix and the intraaxonal compartment. The developed ICT technique associated with a full threedimensional simulation of the axon-aperture near-field system allows a precise measurement of the axon geometry and therefore the direct visualization of neuron swelling induced by temperature change or neurotoxin poisoning.

8812-2, Session 1

Carbazole-based cyanine probes for selective cellular imaging in nonlinear optical microscopy

Mei-Ling Zheng, Technical Institute of Physics and Chemistry (China); Katsumasa Fujita, Osaka Univ. (Japan); Xuan-Ming Duan, Technical Institute of Physics and Chemistry (China); Satoshi Kawata, Osaka Univ. (Japan)

Optical microscopy has been a truly enabling visualization technique in biological and biomedical sciences. Nonlinear optical (NLO) microscopy techniques enable us to reduce photodamage and increase the penetration depth. Additionally, the nonlinear excitation is confined to a focused volume, decreasing phototoxicity and out-of-focus photobleaching. NLO microscopy typically includes two-photon excited fluorescence (TPEF) and second-harmonic generation (SHG). TPEF is a third-order NLO effect that results in an optically confined fluorescence emission. SHG is a second-order NLO effect only observed in non-centrosymmetric structures. While chromophores in general can be excited through TPEF, non-centrosymmetrical arrangements of chromophores are needed for observing an efficient SHG signal. Design strategies towards chromophores for NLO microscopy should combine function and form requirements.

A series of chromophores with enhanced second- and third-order NLO properties was engineered for use in combined SHG and TPEF microscopy. The electron-rich carbazole core serves as a template towards one-dimensional or two-dimensional chromophores. More efficient acceptor groups on the carbazole donor core resulted in the improved second- and third-order NLO properties. A selection of these chromophores was tested in a cellular environment with a multimodal multiphoton microscope. The structural differences of the chromophores resulted in high selectivity for mitochondria or the nucleus in TPEF and ranging from non- to high selectivity for mitochondria in the SHG channel. This study provides prospective applications in tissue, as well as in live animal bioimaging.

8812-3, Session 1

Spectroscopy of site specific DNA assembled plasmonic networks on cell surfaces

Vladimir P. Drachev, Univ. of North Texas (United States); Kyuwan Lee, Joseph M. Irudayaraj, Purdue Univ. (United States)

A new approach has been developed based on DNA- gold nanoparticle network structures as a multiplex probe for both localized surface plasmon resonance (LSPR) and surface-enhanced Raman scattering (SERS) detection [1]. The network structures are well controlled and synthesized by DNA hybridization at specific cell surface sites. The designed network structure improves the sensitivity of the conventional cell surface marker probes to the level of single molecule detection at the membrane of a living cell.

In this paper we discuss optical properties of gold nanoparticle networks for multiplex profiling of human breast epithelial cells to identify the membrane surface markers. The SERS signal of label molecules increases with the number of particles in the network and saturates above 200 particles in the aggregate. The scattering signal detected with the dark field microscopy is also increased for the network relative to a nanorod or nanoparticle of other shape. The peak position is shown to be reproducible for different DNA lengths and number of particles in aggregates and can be extrapolated with a simple equation. The structure can be reversibly controlled by varying the temperature near DNA hybridization melting point. Photothermal effect results in the selective dissociation of nanoparticle structures. The concept of network formation was tested first using antigens and antibody binding reaction on a substrate and then implementing for CD24 and CD44 receptors of three breast cancer cell lines (MCF-7, MDA-MB-231, and MDA-MB-468).

1. K. Lee, V. P. Drachev, and J. Irudayaraj, ACS Nano 5, 2109 (2011).

8812-4, Session 1

Highly fluorescent semiconducting polymer dots for single-molecule imaging and biosensing *(Invited Paper)*

Daniel T Chiu, Wei Sun, Jiangbo Yu, Fangmao Ye, Yu Rong, Univ. of Washington (United States)

This presentation describes the development and application of fluorescent polymeric nanoparticles that we have carried out in our lab in the past several years. I will highlight their photophysical properties and their use in sinlge-molecule microscopy and cellular imaging. We have constructed a number of biosensing systems using these nanoparticles and I will highlight these developments and offer an outlook of their future developments.

8812-5, Session 1

Single plasmonic nanoparticle biosensors for single-molecule and super-resolution imaging of single live cells *(Invited Paper)*

X. Nancy Xu, Old Dominion Univ. (United States)

Noble metal nanoparticles, such as silver nanoparticles (Ag NPs), show distinctive plasmonic optical properties that highly depend upon their sizes, shapes and surrounding environments. These intrinsic plasmonic optical properties enable us to selectively detect and sense single molecules of interest that are specifically recognized by functional molecules attached on the surface of the NPs. Unlike fluorophors and QDs, Ag NPs resist photo- decomposition and blinking, and possess exceptionally high quantum yield of Rayleigh scattering that are orders of magnitude higher than any fluorophors. We have used these intrinsic plasmonic properties of single NPs to develop several new ultrasensitive nanobiotechnologies, including photostable single-molecule-nanoparticle-optical-biosensors (SMNOBS), single nanoparticle plasmonic spectroscopy, and far-field photostable-optical-nanoscopy (PHOTON). We have used these new tools to quantitatively image single protein molecules and study their functions in single live cells with superior temporal and spatial resolutions. We have demonstrated that these powerful new sensing and imaging tools can be used to map

dynamic cascades of membrane transport and signaling transduction pathways of single live cells in real time at single molecule (SM) and nanometer (nm) resolutions. The detailed experimental design and the updated results will be discussed in this presentation. The work is supported in part by NSF (CBET 0507036) and NIH (R01 GM0764401; 3R01 GM076440-04S1).

8812-6, Session 1

Electron-transfer rate in proteins using optical impedance spectroscopy at single-mode waveguides

Xue Han, Sergio B. Mendes, Univ. of Louisville (United States)

An electro-active platform based on a single-mode integrated optical waveguide over coated with a 13-nm indium tin oxide film was developed for highly sensitive investigations on the kinetics of redox reaction of the protein cytochrome-c sub-monolayer under alternating current (AC) potential modulation. 10-mV AC amplitude based on different DC bias with a series of frequencies was applied on spectroelectrochemical cell. 550-nm was selected to probe cytochrome-c absorbance shifting between reduced and oxidized states. Potential and optical signals were recorded by an oscilloscope simultaneously. AC, DC, and phase delay of optical output were analyzed.

Equivalent electrical elements for cytochrome-c redox reaction are an electron transfer resistor Rct in series with a pseudo capacitor Ca. Standard rate constant Ks is expressed in equation 1. After factoring out effects due to optical changes in the working electrode, usually neglected in literature, resonance angular frequency ωr was identified from the reconstructed faradaic current iF in the frequency domain from the modulated optical absorbance signal. iF from different DC bias had the same frequency dependency profile. At -0.08-V DC bias, which had strongest response signal from cytochrome-c, 2.255*10^(-13)-mole/cm^2 AC active surface coverage and 8.697*10^(-7)-A/cm^2 faradaic current density at resonance frequency were observed. A time rate constant of 24.96/s was determined through purely optical signal from the changes in the redox couple.

This high sensitive, accurate, and simple strategy of spectroelectrochemistry is expected to have more potential applications, especially in small electron transfer signal cases.

Ks=1/[(2*Rct *Ca)]=ωr/2 Equation 1

8812-7, Session 1

Addressing biomedicine throughput needs through chip-scale microscopy *(Invited Paper)*

Changhuei Yang, California Institute of Technology (United States)

The pace of microscopy throughput requirement growth in biomedicine is a fast one for which conventional microscopy is ill-suited to address. My group's focus on developing chip-scale microscopy technologies is aimed at addressing this issue by redesigning microscopy from the ground up. In this talk, I will discuss our recent work on 1) the optofluidic microscopy, 2) the ePetri system - a self-imaging petri dish technology that is capable of streaming microscopy images out of an incubator, 3) Talbot microscopy, and 4) Fourier Ptychographic Microscopy. I will discuss the challenges of building a truly compact fluorescence chip--scale microscope and report on the novel strategies we are developing to tackle these challenges.

8812-8, Session 2

Novel optical strategies for biodetection *(Invited Paper)*

Harshini Mukundan, Los Alamos National Lab. (United States)

The biosensor group at the los alamos national laboratory is an interdisciplinary resource of scientists focused on developing solutions to global diagnostic challenges. This presentation will outline some recent advancements of the group, especially towards diagnosis of tuberculosis in patients and detection of E.coli in spinach and beef, using a waveguide based optical biosensor developed by our team. A recent siderophore-based approach to 'fish' for live bacteria will also be discussed. Bringing together synthetic chemistry with optical strategies, novel transduction approaches and nanotechnology to achieve diagnostic success is the focus of this talk.

8812-10, Session 2

Discussion on transmembrane proteins using electrochemically fabricated nanopores

Muhammad S. Khan, Noura S. Dosoky, Debra Moriarity, John D. Williams, The Univ. of Alabama in Huntsville (United States)

Membranes are vital structures found everywhere in the biological system and since last decade nanotechnology has been contributing significant role in many biomedical applications. To probe the chemical and physical properties of transmembrane proteins incorporated with lipid bilayer membrane (LBM), different porous structures (PS) have been used at nanoscale. In this research, we are using porous silicon device to discuss the transmembrane proteins due to its higher surface area to volume ratio. Electrochemical fabrication process will be discussed in detail to fabricate the Nanopores on silicon device. To regulate the flow of ion channels across LBM, two conductive electrodes are used. The Langmuir- Blodgett and Langmuir- Schaefer techniques are used to form the LBM. Scanning Electron Microscopy (SEM) will show images of transmembrane protein on porous structure. Finally, we will present the discussion on using porous silicon membrane to probe the cellular wall of the E. coli bacteria by incorporating different transmembrane proteins on both sides of the porous structure. Advantage of using this methodology is to provide the mechanical stability for the cholesterol free membrane. Future work involves the possibility of integrating the membrane structure with electronic circuitry at nanoscale. Due to the high compatibility of silicon with electronic devices, it can easily be used for many medical and electronic applications. This research will conclude the importance of porous silicon structures which keep the transmembrane proteins in an environment as close as possible to the in-vivo one.

8812-12, Session 2

Hybrid optofluidic integration *(Invited Paper)*

Holger Schmidt, J. W. Parks, H. Cai, D. Ozcelik, S. Liu, Univ. of California, Santa Cruz (United States); L. Zempoaltecatl, Aaron R. Hawkins, Brigham Young Univ. (United States)

We will discuss the hybrid integration of silicon-based optofluidic waveguide devices with additional structures and layers in order to enhance optical detection and manipulation on the single particle level. Specifically, we describe the vertical integration of a microfluidic layer that performs dedicated microfluidic sample handling functions such as analyte mixing, distribution, and filtering. We will also discuss the incorporation of a nanopore-based electrical sensor with the optical detection platform. This combination enables multimodal, correlated detection, discrimination, and analysis of individual nanoparticles.

8812-13, Session 2

Viscoelastic property of the cell membrane influenced by the adhesion of macrophages on the matrix extracellular

Samuel T. Souza, Lais C. Agra, Emiliano Barreto, Jandir M. Hickmann, Eduardo J. da Silva Fonseca, Univ. Federal de Alagoas (Brazil)

Macrophages have important roles in the immune response and tissue homeostasis. Its capacity for phagocytosis renders them effective at patrolling through a variety of tissues. In addition, the hallmarks of activation of macrophages can be verified by cell adhesion and spreading on extracellular matrix (ECM). Among the ECM components, fibronectin has been recognized as the key element in promoting cell adhesion and various functions of macrophages. However, yet is not fully understood if the deformation capacity of the membrane plasmatic is influenced by cell adhesion on the ECM.

In this work we studied viscoelastic properties of the macrophages membrane adhered on a film of fibronectin using the Atomic Force Microscopy (AFM) aiming to identify possible interference of extracellular matrix on the biomechanical characteristics of cells. To this study, J774 macrophages were incubated for 1h and 48h on glass coverslips and on glass coverslips recovered with EMC. After 1h or 48h of incubation, cells were fixed and analyzed with the AFM nanoindentation technique.

Ours results have revealed that no significant variation in Young's modulus of cells incubated just on glass coverslips for 1h and 48h. However, they showed the increase in the Young's modulus of about 36% and 50% for cells incubated on glass coverslips recovered with EMC, respectively, as compared with cells incubated just on glass coverslip for 1 and 48h.

In summary, ours results indicate that cell adhesion on fibronectin induce a significant alterations on viscoelastic properties of the cell membrane, suggesting involvement of the intracellular components, such as cytoskeleton, triggered by interaction between cell and ECM.

8812-14, Session 2

Nano-engineered titanium for enhanced bone therapy

Karan Gulati, Gerald Atkins, David Findlay, Dusan Losic, The Univ. of Adelaide (Australia)

Natural bone is a perfect example of nanoengineering, which often requires support in the form of therapies, implants or corrections for conditions that are beyond the scope of normal repair. Bone cancer, severe fractures, osteoarthritis, and bone infection requires special assistance: chemo/radiotherapy, grafting/correction, protein/hormone administration and antibiotic therapy respectively. These often affect the healthy tissues while the dose at the target site remains ineffective; ultimately leading to exacerbated effects: bone loss, re-surgery and need to amputate. The possible solution to treating such bone conditions is local drug delivery i.e. delivery of therapeutics directly at the site where it is desired.

To achieve effective bone therapy we propose fabrication of titanium implants capable of releasing the loaded drug/protein for extended durations following favorable kinetics. Titanium substrates were modified using electrochemical anodisation to fabricate array of self-ordered hollow titania ($TiO2$) nanotubes (TNTs). In-vitro drug release studies depicted substantial loading amounts and delayed release patterns for anti-bacterial, anti-inflammatory and anti-cancer drugs. To further delay the release of therapeutics to over 30 days a thin layer of biopolymer was coated onto the drug loaded TNTs. Biocompatibility studies with osteoblast cells demonstrated enhanced cell adhesion and proliferation; which directly relates to bone forming ability.

Results demonstrated ability to load wide variety of therapeutics inside these implants with delayed release patterns. Also the dimensions of the TNTs and the biopolymer coating thickness could be tailored to accommodate more drug amount and control the release behavior. The proposed technology can easily be applied for bone therapies/fixation for the infected/fractured bone for mechanical support, with 3D release of drug inside the bone micro-environment and enhanced bone cell functions; making the proposed system suitable to target hard-to-reach bone conditions like: infection and cancer.

8812-15, Session 2

Acute toxicity of rattle-type silica nanorattles coated gold nanoparticles in intravenously exposed mice

Tianlong Liu, Longfei Tan, Technical Institute of Physics and Chemistry (China); Dong Chen, Beijing Creative Nanophase Hi-Tech Co., Ltd. (China); Huiyu Liu, Linlin Li, Changhui Fu, Tianlong Tang, Technical Institute of Physics and Chemistry (China)

Gold nanoparticles is a promising nanomaterials used in the field of biological imaging, cancer diagnosis and treatment. With the rapid increase of nanomaterials applications, the concerns on the health impacts caused by nanomaterials are also increasing [1-3]. In this paper, we synthesized a novel nanostructure in which 13 nm gold nanoparticles exist in the cavity of the core-shell silica structure (SN@GN) and the single dose toxicity, and biodistribution of SN@GN in vivo were demonstrated after intravenous injection in mice. Silica nanorattle are emerging as one of the new and promising nanomaterials for biomedical applications, and our previous study suggest low lethal toxicity of MHSNs when intravenous injection at single dose or repeated administrations [4-5]. For single dose toxicity, lethal dose 50 (LD50) of SN@GN was higher than 500 mg/kg. ALT and AST were elevated in SN@GN treated mice over 160 mg/kg dose, however, levels in vehicle and 80 mg/kg were comparably low. Histological analysis revealed lymphocytic infiltration in liver and lung of high-dose SN@GN treated mice. ICP-OES, TEM and dark field imaging results show that the SN@GN mainly accumulates in mononuclear phagocytic cells in lung, liver and spleen. These findings would be useful for future development of nanotechnology-based drug delivery system and other biomedical applications.

8812-16, Session 2

Magnetic particles and cyanoacrylate-based glue for intraluminal bowel retraction

Pascal André, Univ. of St. Andrews (United Kingdom); Zhigang Wang, Univ. of Dundee (United Kingdom); Ipek Birced, Univ. of St Andrews (United Kingdom); Andrew Brown, Stuart I. Brown, Univ. of Dundee (United Kingdom); Gordon J. Florence, Univ. of St Andrews (United Kingdom); Alfred Cuschieri, Univ. of Dundee (United Kingdom)

Reducing tissue trauma is needed for surgery applications when physical retraction is completed with graspers.[1-2] In this medical field, small magnets have been used for magnetic tissue retraction[3-5], however magnetic particles offers further advantages.[6-7] In this presentation, we will describe a novel method of magnetisation of bowel segments by intraluminal injection of magnetic glue.

Following materials' characterisation studies, micro-particles of stainless steel and iron oxide nanoparticles could be mixed with medical grade cyanoacrylate glues to design an injectable magnetic media suitable for surgery applications. During intra-luminal injection of the magnetic glue using ex-vivo porcine colonic segments, a magnetic probe placed at the injected site ensured that the particles dispersed in the glue as it polymerized to form an intra-luminal mucosally-adherent coagulum. This report will show how the magnetized porcine colonic segments can be retracted by magnetic probes placed external to the bowel wall. A tensiometer was used to record the retraction force and distance.

The results of this study indicate that the formation of an intra-luminal coagulum produces sufficient magnetic retraction for bowel retraction. This ex-vivo study requires confirmation by in-vivo animal studies before clinical translation to Minimal Access Surgery.

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8812-17, Session 2

Single nanoparticle sensing using whispering-gallery microresonators and microlasers

(Invited Paper)

Lan Yang, Jiangang Zhu, Sahin K. Ozdemir, Lina He, Woosung Kim, Huzeyfe Yilmaz, Faraz Monifi, Steven H. Huang, Washington Univ. in St. Louis (United States)

Microsystems for detecting biomolecules will play important roles in biomedical research, clinical diagnosis, food safety, pharmaceutical testing, and environmental monitoring. Optical sensors based on Whispering-Gallery-Mode (WGM) resonators have emerged as front-runners for label-free, ultra-sensitive detection of nanomaterials and nanoscale phenomena due to their superior capability to significantly enhance the interactions of light with the sensing targets by confining light photons in small volumes for long periods of time. A WGM resonator traps light in circular orbits in a way similar to a whisper, i.e., a sound wave, traveling along a circular wall, an effect found in the whispering gallery of St. Paul's Cathedral in London. This talk will introduce ultra-high-quality (Q) optical WGM microresonators and their fabrication process. The basis for resonator sensors is that the physical associations and interactions of nanomaterials on the surface of a high-Q optical WGM resonator alter the trajectory and lifetime of photons in a way that can be measured and quantified. I will present a recent discovery of using ultra-high-Q microresonators and microlasers for ultra-sensitive self-referencing detection and sizing of single virion, dielectric and metallic nanoparticles. I will discuss using optical gains in a microlaser to improve the detection limit beyond the reach of a passive microresonator. These recent advancements in WGM microresonators will enable a new class of ultra-sensitive and low-power sensors for investigating the properties and kinetic behaviors of nanomaterials, nanostructures, and nanoscale phenomena.

8812-18, Session 2

Single-beam optical biosensing using laser nanopolymerization and enzyme reactions

Hiroyuki Yoshikawa, Shuhei Imura, Eiichi Tamiya, Osaka Univ. (Japan)

We found a characteristic modulation of the backreflected laser intensity induced by focusing a laser beam on an o-PD solution, and we applied this phenomenon to glucose detection. Because enzyme reactions using peroxidase are widely used for biosensing applications, particularly in enzyme-linked immunosorbent assays (ELISAs), this technique should also be applicable to various biosensors. A reliable optical quantification of glucose can be performed in a short time (~2 min including incubation) with a small sample volume (<20 μL). In addition, the sensing system can be constructed by using simple components without requiring any complex optics and expensive spectroscopic detectors. Furthermore, laser focusing and backreflection detection are simple techniques that are even performed by the read/write heads, known as an optical (or laser) pickup, of optical storage drives. This suggests that this biosensing technique is promising for developing compact and inexpensive optical biosensors for widespread applications to point-of-care monitoring.

8812-19, Session 2

Silica nanorattle and gold nanoshell on silica nanorattle for cancer therapy

Fangqiong Tang, Huiyu Liu, Linlin Li, Tianlong Liu, Technical Institute of Physics and Chemistry (China); Dong Chen, Beijing Creative Nanophase Hi-Tech Co., Ltd. (China)

For decades, nanomedicine has brought new opportunities for cancer therapy. Drug delivery systems based on nanomaterials have been proved to improve inherent limitations of classical pharmacotherapy. Recently, mesoporous silica nanomaterials (MSNs) have attracted more and more attentions for biomedical application especially for drug delivery. As nanocarriers, mes¬oporous silica nanoparticles with unique mesoporous structure have been explored as effective drug delivery systems for a variety of therapeutic agents to fight against various kinds of diseases including bone/tendon tissue engineering, dia¬betes, inflammation, and cancer. Furthermore, it provides unique opportunities for simultaneous diagnosis and therapy with the MSN-based multifunctional nanocomposites not only as drug delivery system but also as an imaging modality. Recently, near-infrared (NIR) resonant nanomaterials, such as gold nanoshells, gold nanorods and carbon nanotubes, have been used for hyperthermia under photothermal treatment (650-900nm). Multifunctional nanocomposites that integrate these special nanomaterials into one system have attracted much attention for their potentials in simultaneous disease diagnosis and therapy. However, it's great challenges to successfully fabricate the nanocomposites and optimize their performance. In this paper, our researches demenstrate that the silica nanorattles and the multifunctional counterparts can to be developed as versatile nanoformulations promising for clinical applications in cancer diagnosis and therapy. It may provide useful information for the development of novel drug delivery system based on mesoporous silica nanomaterials.

8812-20, Session 2

Use of novel silver nanoparticles with hyaluronan as potential biological labels for determine the quality of embryos development

Vasyl J. Syrvatka, Yurij I. Slyvchuk, Institute of Animal Biology NAAS (Ukraine); Oleksandr I. Bilyi, Ivan Franko National Univ. of L'viv (Ukraine); Ivan I. Rozgoni, Ivan I. Hevkan, Institute of Animal Biology NAAS (Ukraine)

In reproductive medicine it is important to determine the quality of embryo development without interference in their function and viability. Unique plasmon-resonant optical properties of silver nanoparticles make them promising candidates for use in nanomedicine as signal enhancers, optical sensors and biomarkers. The main aim of the study was to investigate the physicochemical properties and biological activities of novel functional silver nanoparticles with prospect of their use in embryo transfer techniques as diagnostic and sensing tools.

For this purpose, we synthesized new silver nanoparticles with hyaluronan by chemical reduction method. The physical and biological properties of novel silver nanoparticles were compared with silver nanoparticles identical in size and shapes but with different chemical surfaces modifications by polyvinylpyrrolidone and bovine serum albumin. We used transmission electron microscopy and ultraviolet-

visible spectroscopy techniques for structural characterizations of nanoparticles. The antimicrobial activities of the composite nanoparticles were determined by measurement of their minimum inhibitory concentrations. In addition, we studied the influence of different concentration of composite silver nanoparticles on rabbit's embryo development in vitro.

Our results show that novel silver nanoparticles have distinct physicochemical properties and level of degradation in culture medium versus to nanoparticles with polyvinylpyrrolidone and bovine serum albumin. Furthermore, biological activity on Gram positive and Gram negative bacteria and toxicity on rabbit's embryos was different in nanoparticles with different surface modification. Therefore, the novel silver nanoparticles with hyaluronan have unique physicochemical properties and biological activity and can be applied in reproductive medicine as diagnostic and sensing tools.

8812-23, Session 2

Silica nanorattle as drug carrier for cancer targeting therapy

Linlin Li, Tianlong Liu, Technical Institute of Physics and Chemistry (China); Dong Chen, Beijing Creative Nanophase Hi-Tech Co., Ltd. (China); Huiyu Liu, Longfei Tan, Changhui Fu, Fangqiong Tang, Technical Institute of Physics and Chemistry (China)

Mesoporous silica nanomaterials (MSNs) have attracted more and more attention for bioapplication especially for drug delivery.[1] We have synthesized a novel kind of mesoporous and hollow nanomaterials: slilica nanorattles (SN).[2] It have good monodispersion, controllable size, mesoporous and hollow structure and high specific surface area. The silica nanorattles with suitable size and structure were developed as drug delivery systems for anticancer drug of decetaxel for in vitro and in vivo liver cancer therapy. The results prove that the silica nanorattles have potentials to enhance the therapy efficacy and reduce the systemetic toxicity of the drugs.[3] For better tumour targeting, targeting ligand of folic acid[4] and luteinizing hormone-releasing hormone-Pseudomonas aeruginosa exotoxin 40 (LHRH-PE40) was bioconjugated onto the silica nanorattle for targeted imaging and therapy of ovarian carcinoma and lung cancer, respectively. In addition, we designed a more active targeting strategy. Mesenchymal stem cells (MSC), which have a tropism for brain tumor, were used for acting as delivery vehicles of drug loaded silica nanorattle for targeting therapy of glioma.[4] The combination of "stem cell targeting" and "controlled drug delivery" has promising to target and kill all the tumor cells including the primary and metastasis satellites. These results may provide useful information for the development of new strategies for the design of efficient drug delivery nanocarriers and therapeutic system.

8812-21, Session 3

Plasmonic engineering in nanomedicine *(Invited Paper)*

Srikanth Singamaneni, Washington Univ. in St. Louis (United States)

High refractive index sensitivity of localized surface plasmon resonance (LSPR) of metal nanostructures renders them as attractive nanotransducers for point-of-care biodiagnostics. However, most of the current plasmonic biosensors rely on natural antibodies for biorecognition and rigid substrates for device fabrication. These conventional methods are not ideal for translation of plasmonic biosensors to resource-limited and point-of-care settings. We demonstrate that a common a filter paper loaded with biofunctionalized metal nanoparticles enables the detection of target disease biomarkers in complex physiological fluids. Apart from significantly lowering the cost, such bioplasmonic paper is ideal for translating bioplasmonic paper to resource-limited settings. Furthermore, we also demonstrate that natural antibodies, which suffer from numerous shortcomings such as limited environmental and chemical stability can be replaced with artificial antibodies by molecularly imprinting the plasmonic nanostructures. In the second part of this talk, we present a novel class of ultrabright surface enhanced Raman scattering (SERS) probes, which we call Bi-layered Raman-intense Gold nanostructures with Hidden Tags (BRIGHTs). These novel SERS probes are nearly 20 times brighter compared to the conventional SERS probes and enable rapid molecular bioimaging of breast cancer cells.

8812-22, Session 3

Optical methods for wireless implantable sensing platforms

Muhammad Mujeeb-U-Rahman, Chieh-Feng Chang, Axel Scherer, California Institute of Technology (United States)

Fully Wireless Implantable platforms for sensing and actuation have gained importance for many applications recently. These systems can be used for both corrective health care and biological applications. To be able to work as long-term devices, these need to be designed on very small size scales and need to be fully wireless to avoid foreign body reaction and the risk of infection due to wires. Optical methods are very attractive for such systems due to the small footprint of optical devices and due to inherent decoupling between optics and signal processing circuits used in such systems. Here we present techniques to remotely power such systems using Photovoltaic power supply. We will show designs optimized for such applications which require high voltages (higher than the built-in potentials of the substrate materials) and designs optimized for high current requirements. We will provide theoretical and experimental results of such power harvesting systems and how these can be tuned for different applications. We will show examples of integrated designs in standard CMOS processes and see how these compare to theoretical results for Silicon based Photovoltaic devices. We will also show results from small-scale compound semiconductor Photovoltaic devices and their integration with the Silicon based sensing systems. We will also include design of Silicon-on-Insulator based Photovoltaic systems and methods to increase optical path lengths in such devices to increase their efficiency. Finally, we will show experimental results using Photovoltaic devices embedded in biological media and discuss the effect of optical methods on their surrounding media.

8812-24, Session 3

Size-dependent nanoparticle delivery by biodegradable microsphere-mediated perforation using femtosecond laser

Tatsuki Mitsuhashi, Mitsuhiro Terakawa, Keio Univ. (Japan)

A combination of nano/microparticles and laser irradiation is promising for drug delivery and theranostics. However, nano/microspheres have concerns with regards to the potential cell toxicity which is mainly dependent on their material and size. We have been studying cell membrane perforation using an enhanced optical field around a biodegradable sphere excited by a near-infrared femtosecond laser. In this study, with the purpose of achieving a size selective drug delivery using biodegradable polymer, we investigated the size of the particles that can be delivered into cells and discussed the governing mechanism. FITC-labeled silicon nanoparticles of different sizes were used in this study and obtained that the efficiency of cellular delivery decreased with increasing the particles' diameter. However, particles up to 100 nm in diameter were able to be delivered. By observing the emission spectra, we elucidated that the breakdown of water is necessary to obtain a high efficiency. The effect of a charge of the silicon particles on the efficiency will also be presented. This study contributes to developing a safe high throughput size selective drug delivery using biodegradable polymer spheres.

8812-25, Session 3

Nanoimprinted optical biosensor for diagnostics and biomimetic lung-on-a-chip for drug studies *(Invited Paper)*

Sonia Grego, RTI International (United States)

(Invited) Engineered devices leveraging micro- and nano-technology enable novel solutions for significant diagnostic and therapeutic applications such as point-of-care detection of infectious diseases and biomimetic cellular models of human organs for drug studies.

Optical biosensors represent rapid and compact analytical tools. Field-deployable platforms are high desirable for applications such as diagnosis of infection from a clinical specimen yet many of the recently developed optical biosensors are limited to laboratory use due to the large size and complexity of the read-out system. The Tunable Wavelength Interrogated Sensor Technology (TWIST) relies on a device and system designed for a compact and rugged biosensor platform. The sensing device is a grating-integrated optical waveguide obtained by nanoimprint lithography with an inexpensive stamp. The TWIST configuration and performance, including on-chip reference, will be described, and its application to infection disease diagnostics will be discussed.

The development of new therapeutics is poised to greatly benefit from microfluidic devices enabling biomimetic cell cultures. Engineered cell-cultures reconstitute physiological organ functions and, therefore, more closely emulate tissue response to drugs and insults. The lung is a primary site of exposure to pathogens as well as an attractive drug delivery route. This talk will describe a sophisticated microfluidic lung model which recapitulates key features of the function and morphology of airway epithelium. This lung cellular construct relies on the use of highly differentiated human primary cells and it is enabled by a multilayer device designed to ensure optimal cell differentiation and to reproduce physiological interfaces between cell types.

8812-26, Session 3

Smart integrated optical sensor patch dedicated to wireless real-time brain-machine interface and body area networks

Ehsan Kamrani, Seok Hyun A. Yun, Wellman Ctr. for Photomedicine (United States)

REMOTE control of ambient tools using thought has been a dream falsified in several science fiction stories. Available human-machine interfaces (HMIs) use bulky systems and invasively implanted electrodes to monitor and transfer brain signals. Portable and real-time non-invasive brain imaging using functional near-infra-red spectroscopy (fNIRS) provide ability of translating brain commands appears in the form of hemodynamic and neural dynamics to the electric signals. Some recent works have applied fNIRS and its combination with electro encephalogram (EEG) in HMIs and human brain studies, however they suffers from bulky, wired, difficult to setup, and low signal-to-nose ratio (SNR) photodetector front-end, in additional to their infeasibility to be applied for continues and real-time monitoring due to the power and speed limitations they are suffering. These drawbacks also have impeded attaching optical monitoring tools such as pulse-oximetry and fNIRS to be used in the body area networks (BANs).

Here we introduce an ultra-miniaturized (~5 g weight and ~1 [cm]^2 housing) wireless patch for real-time monitoring, processing and transponding of brain signals. It records and decodes the electro-optical brain signals using a small optical sensor patch without implanting electrodes. It includes two LEDs and a driver, silicon avalanche photodiode (SiAPD), photodetector front-end, analog-to-digital converter (ADC), signal processing unit and an ultra-low power RF transceiver, on-chip and wirelessly powered. The low power consumption (less than 5mW) makes this miniature patch a proper candidate to be applied in BAN. The wireless link can afford up to 5 m distances with high data-rate (10 MHz) and low noise. This patch provides also an optional wireless communication with cell-phone. One can control the patch function and also monitor the signals on any ordinary smart cell-phone. In contrast to the available monitoring tools providing vital information only from specific regions of human body, this new plug-and play device can monitor and delivers signals from different locations of the whole human body. It can be placed as a brain-computer interface (BCI) in patients with spinal cord injuries to make them possible to control external devices, such as a computer cursor or a prosthetic limb, assistive devices, etc. with their thoughts. The neural activity picked up by the BCI will be translated using on-chip processing unit, allowing the patient to learn to control computer interfaces (cursors, monitor,…) and assistive devices such as a prosthetic hand or a wheelchair.

The prototype of the photo-transceiver is implemented and the work is ongoing on wireless control and transmission implementation and its clinical demonstration and assessment.

8812-27, Session 3

Nano-cone optical fiber array sensors for miRNA profiling

Yunshan Wang, Hsueh-Chia Chang, Satyajyoti Senapati, Univ. of Notre Dame (United States); Paul R. Stoddart, Swinburne Univ. of Technology (Australia); Scott S. Howard, Univ. of Notre Dame (United States)

Up/down regulation of microRNA panels has been correlated to cardiovascular diseases and cancer. Frequent miRNA profiling at home can hence allow early cancer diagnosis and close chronic disease monitoring, thus reducing both mortality rate and healthcare cost. However, lifetime of miRNAs is less than 1 hour without preservation and their concentrations range from pM to mM. Despite rapid progress in the last decade, modern nucleic acid analysis methods still do not allow personalized miRNA profiling. Real-time PCR and DNA micro-array both require elaborate miRNA preservation steps –and expensive equipment.

We report a novel and low-cost optical fiber sensing platform, which has the potential to profile a panel of miRNA with simple LED light sources and detectors. The individual tips of an optical imaging fiber bundle (mm in diameter with 7000 fiber cores) were etched into cones with 10 nm radius of curvature and coated with Au. FRET (Forster Resonant Energy Transfer) hairpin oligo probes, with the loop complementary to a specific miRNA that can release the hairpin, were functionalized onto the conic tips. Exciting light in the optical fiber waveguide is optimally coupled to surface plasmonics on the gold surface, which then converges to the conic tips with two orders of magnitude enhancement in intensity. Unlike nanoparticle plasmonics, tip plasmonics can be excited over a large band width and hence the plasmonic enhanced fluorescence signal of the FRET reporter is also focused towards the tip--- and is further enhanced with the periodic resonant grid of the fiber array which gives rise to pronounced standing wave interference patterns. Multiplexing is realized by functionalizing different probes onto one fiber bundle using a photoactivation process. The net result is a plasmonic sensor for miRNA profiling with a dynamic range from one to one thousand miRNA molecules per tip (up to one million over 1000 tips) with more than 5 miRNA targets per fiber bundle.

8812-29, Session 3

Nanoplasmonics approaches to biosensing *(Invited Paper)*

Reuven Gordon, Univ. of Victoria (Canada)

This talk will overview our recent advances towards ultrasensitive nanohole array SPR, directivity enhanced Raman scattering (DERS) for reliable single molecule level detection, and optical manipulation of single proteins. Applications to immunoassays and the early detection of cancers will be presented.

8812-30, Session 3

Focused cylindrical vector beam assisted microscopic phase-sensitive surface plasmon resonance biosensor

Chonglei Zhang, Rong Wang, Xiaocong Yuan, Nankai Univ. (China)

We designed and proposed a microscopic configuration of wide-dynamic-range phase-sensitive surface Plasmon resonance biosensor based on differential interferometry between focused radially polarized and azimuthally polarized cylindrical vector beams recently. This system not only with a sensitivity of 7.385E-7refractive index unit (RIU)/0.1,but also verified that the dynamic range of this system could be as large as 0.35 RIU. Due to the system is based on the microscopic configuration, could be used to imaging by scanning, the resolution is about 200nm, less than diffraction limit because of the tight-focus characteristic of cylindrical vector beam. We use the system to detect the cytoskeletal, antigen-antibody reaction and so on.

8812-31, Session 3

Hybrid waveguide based long range surface plasmon biosensor

Youqiao Ma, Dublin Institute of Technology (Ireland)

In this paper, an integrated biosensor based on a hybrid coupler consisting of a dielectric waveguide and a long range surface plasmon polaritons (LRSPPs) waveguide is proposed. The influence of the structural parameters of the biosensor is investigated using a finite element method (FEM). By appropriately selecting the waveguide parameters, the propagation constants between LRSPPs and waveguide (WG) modes can be matched, along with the light coupling between WG and LRSPPs modes, which in turn allows the sensitivity to be optimized. The resonant coupling wavelength between WG and LRSPPs modes is very sensitive to surrounding refractive index changes in the vicinity of the metal surface, with an estimated sensitivity of 4180 nm/RIU (refractive index unit). This is marginally higher than the value of 3750 nm/RIU in the same RI range from 1.33 to 1.34 reported in reference [1] for optical biosensing applications. However compared to [1] our proposed structure has the advantage that it is inherently easier to introduce an analyte into our structure.

[1] E. K. Akowuah, T. Gorman, and S. Haxha, Design and optimization of a novel surface plasmon resonance biosensor based on Otto configuration, Opt. Express 17, 23511-23521 (2009).

8812-11, Session PWed

Design and fabrication of silicon-based optofluidic waveguide platforms *(Invited Paper)*

Aaron R. Hawkins, Brigham Young Univ. (United States)

Using silicon-based microfabrication and materials we have developed a photonic platform capable of single bioparticle analysis. This platform combines liquid and hollow core waveguides on the micron-scale (5x12 μm) to isolate femtoliter sized sample volumes. Fluorescence excitation and emission signals in the visible range are directed into and out of the sample volume at orthogonal angles to maximize signal-to-noise. This paper reveals the development path of these structures over several device generations including innovations in material, geometries, and fabrication techniques to increase detection sensitivity.

8812-33, Session PWed

Encapsulating gold nanoparticles in silica hollow nanospheres for in vitro and in vivo dark field imaging

Longfei Tan, Dong Chen, Fangqiong Tang, Technical Institute of Physics and Chemistry (China)

Nanostructures with interstitial hollow space and mesoporous shell have low density, high specific area and permeable porous shell for the penetrating of guest species, which are ideal for drug carriers.[1] Due to their biocompatibility, low toxicity, high chemical and mechanical stabilities, silica hollow nanospheres have show great potential in drug delivery application[2]. Recently, rattle-type nanostructures, a kind of hollow nanostructures with metal core, were attracted more attention because of their potential to integrate optical, magnetic and electronic properties in one. Gold nanoparticles is a promising nanomaterials used in the field of biological imaging, cancer diagnosis and treatment.[3,4] Encapsulating gold nanoparticles in silica hollow nanospheres will offer fascinating tuned surface plasmon resonance (SPR) properties, which make them ideal materials for drug delivery and bio-imaging.[5] In this work, we synthesized a novel nanostructure in which 13 nm gold nanoparticles encapsulated in the cavity of the silica hollow nanospheres (Au@SiO2). The presence of silica shell protects gold cores in complex biological environments, ensures their dark field imaging characteristics both in vitro and in vivo. These Au@SiO2 nanospheres also exhibit higher drug loading capacity and desired release rates due to their hollow cavity and mesoporous shell. Cytotoxicity experiments show good biocompatibility of Au@SiO2 in vitro. Acute toxicity in mice showed that the maximum tolerated dose of Au@SiO2 greater than 200 mg/kg, significantly improve the biocompatibility of gold nanoparticles. Encapsulating gold Nanoparticles in silica hollow nanospheres is expected to have great potential in medical imaging and therapy application.

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8812-34, Session PWed

Molecular detection for multiple cancer biomarkers using multi-tasking localized surface plasmon resonance sensor

Yoochan Hong, Yonsei Univ. (Korea, Republic of); Jin-Suck Suh, Yong-Min Huh, Yonsei Univ. College of Medicine (Korea, Republic of); Dae-Sung Yoon, Yonsei Univ. (Korea, Republic of); Jaemoon Yang, Yonsei Univ. College of Medicine (Korea, Republic of)

The noble metal nanoparticles, such as gold or silver, are used as sensing substrate because of the collective oscillations of their conduction band electrons. This phenomenon is called as localized surface plasmon resonance (LSPR). The basic LSPR effect has been long understood, the field has experienced significant growth recent 10 years due to advances in the nanotechnology. More recently, LSPR-based nanobiosensors were developed as tools for highly sensitive, label-free, and flexible sensing techniques for the detection of biomolecular interaction. Herein, we describe that development of LSPR nanobiosensor, which can detect adsorption of protein onto sensor substrate and cleavage of enzyme specific targetable peptide from the sensor substrate simultaneously. When the protein extracted from cancer cells adsorbed onto sensing substrate, the LSPR signal was red-shifted, and in the case of the enzyme, as enzyme specific targetable peptide was cleaved, we observed that LSPR signal was blue-shifted. First of all, we prepared sensing substrate that composed of different nanoparticles which have significantly distinct plasmonic band gaps. Subsequently, for specific detection of biomarker, CD44, a receptor expressed on cancer cell surface, we used specific targeting antibody, and we also conjugated for detection of another biomarker, MT1-MMP, the enzyme expressed on invasive cancer cells.

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8812-35, Session PWed

The interactions of the carbon-based nanoparticles with HeLa cell's plasma membrane

Marta Overchuk, Tanya Dumych, Institute of Cell Biology (Ukraine); Svitlana Prylutska, Yuriy Prylutsky, National Taras Shevchenko Univ. of Kyiv (Ukraine); Rostyslav O. Bilyy, Institute of Cell Biology (Ukraine)

The study of carbon-based nanostructures is a highly topical branch of bionanotechnology because of their potential application in biomedicine. Carbon-based nanotubes (CNT) are known for their ability to kill tumor cells causing hyperthermia shock. Fullerens are regarded as valuable nanocarriers for antitumor drug delivery, as they possess strong antioxidant properties. Chemically modified CNT also can be used for drug delivery. The needle-like shape of CNT lets them penetrate the cell's plasma membrane without killing the cell.

In the current work the interactions of pristine C60 fullerens and multi-walled carbon nanotubes filed with (MWCNT-Fe) iron with cell's plasma membrane were studied. The interactions were analyzed in the cell-nanopartice system. It was shown, that both MWCNT-Fe and C60 fullerens tend to form pores, channels or other types of local defects in the plasma membrane, that are wide enough to let the passage of water into the cell. The application of high resolution DIC and fluorescent microscopy demonstrated the externalization of phosphatidylserine (PS) from the inner to outer layer of the cell membrane in small local patches (points of contact), while other parts of plasma membrane being PS-negative. The externalization of PS was visualized with a use of Annexin-V staining, a fluorescent dye, that binds specifically to PS.

8812-36, Session PWed

Azimuthally-invariant Mueller-matrix mapping of biological tissue in differential diagnosis of mechanisms protein molecules networks anisotropy

Volodimir G. Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

At present, the biological and medical research using many practical techniques based on the measurement and analysis of the Mueller matrices of the samples. Not all elements of the Mueller matrix are convenient to characterize the sample of biological tissue - generally, 12 of the 16 elements is change when the sample is rotated around the axis sensing. This paper shows that the azimuthally stable, independent of the angle ( ) rotation of the sample, the following are the elements of of Mueller matrix.

Set a maximum sensitivity of higher order statistical moments that characterize Muller - matrix invariants by linear and circular birefringence, the morphological features of the molecular structure of biological tissues protein networks.

8812-37, Session PWed

Laser polarization fluorescence of optically anisotropic crystals molecular imaging in the differentiation of biological benign and malignant tumors

Alexander V. Dubolazov, Yuriy A. Ushenko, Artem O. Karachevtsev, Artem V. Motrich, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

In the current scientific literature is almost no data on the effects of fluorescence polarization forms in tissues. Therefore, the actual problem is in combining diagnostic capabilities of laser polarimetry and laser fluorescence. In this paper we propose a model of laser polarization of biological tissues fluorescence molecular imaging with the mechanisms of the optically anisotropic absorption, - linear and circular dichroism in protein networks.

Effectiveness of the method azimuthally - invariant Mueller - matrix mapping laser polarization of fluorescence molecular imaging of protein networks in the problem of differentiation of benign and malignant tumors of the uterine wall was demonstrated.

8812-38, Session PWed

Detection of saccharides with a fluorescent sensing device based on a gold film modified with 4-mercaptophenylboronic acid monolayer

Shu-Jen Chen, Jui-Feng Chang, Nai-Jen Cheng, Jeng-Nan Yih, National Kaohsiung Univ. of Applied Sciences (Taiwan); Kuo-Chi Chiu, Industrial Technology Research Institute (Taiwan)

An extremely sensitive fluorescent sensor based on a phenylboronic acid monolayer was developed for detecting saccharide molecules. The fluorescent sensor was prepared by assembling a monolayer of 4-mercaptophenylboronic acid (4-MPBA) onto a gold-coated compact disk. The change in the fluorescence of the 4-MPBA monolayer was extremely obvious in basic methanolic buffer containing monosaccharides down to the picomolar level. The fluorescence spectra demonstrated that the 4-MPBA monolayer was sensitive to monosaccharides and disaccharides, and the affinity of the monolayer toward saccharides was in the order of glucose > fructose > mannose > galactose > maltose > lactose > sucrose. Additionally, the fluorescence intensity of 4-MPBA monolayer was restorable after cleaning with weak acid, indicating that the reported fluorescent sensor with the detection limit of glucose down to the picomolar level is reusable for sensing saccharides.

8812-39, Session PWed

Photothermal ablation of metastatic cancer cells using magnetic polyaniline nanocomposite guided by MR imaging

Seungyeon Hwang, Dan Heo, Yoochan Hong, Minhee Ku, Eugene Lee, Seungjoo Haam, Jin-Suck Suh, Jaemoon Yang, Yonsei Univ. (Korea, Republic of)

For effective treatment of invasive cancer, photothermal therapy based on nanoparticles has been reported as representative method. In recent, polyaniline has been used as a photothermal agent in our research group, because it can absorb the light of near-infrared (NIR) region, then generates a substantial amount of heat energy that can be used for cancer cell ablation. To diagnose cancer cell, on the other hand, magnetic nanoparticles have used in magnetic resonance (MR) imaging agents. From these facts, we synthesized a magnetic polyaniline nanocomposite (MPNC) for photothermal therapy guided by MR imaging. MPNC was synthesized using iron-acetylacetonate and polyaniline by thermal-decomposition method without any additive ligands. To detect membrane type 1 metalloproteinase (MT1-MMP), subsequently, the surface of MPNC was PEGylated and modified with MT1-MMP-specific targetable peptide. To confirm fundamental characteristics of MPNC, colloidal size using dynamic light scattering, NIR absorption using spectrometer, morphology using transmission electron microscope, and magnetic property using vibrating sample magnetometer were evaluated. To estimate MR imaging potential and photothermal ablation capability of MPNC for target cancer cell, MPNC was intravenously injected into the tumor-bearing mice. The invasive cancer cells, treated with MT1-MMP-specific MPNC, were detected by MRI and broken down and damaged after irradiation of NIR light.

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8812-40, Session PWed

Raman laser-based detection of mode splitting in a high-Q microcavity

Bei-Bei Li, Qihuang Gong, Yun-Feng Xiao, Peking Univ. (China)

No Abstract Available

8812-41, Session PWed

Metalorganic magnetic nanoparticles as a targeted drug delivery system of Gd3+ for neutron-capture therapy against cancer

Olga V. Kondrashina, Voronezh State Univ. (Russian Federation)

The challenge in successful neutron-capture therapy against cancer depends has been the ability keep proper

concentration of Gd in tumor tissues during the irradiation. We developed a new method of producing nanoparticles based on cholesteric liquid crystal DNA-dispersion complexed with Gd in very high local concentration of gadolinium ions (up to 400 mg/ml inside particles). Their magnetic properties lead to active diffusion of Gd in tissue with the help of a strong magnetic field and keep those nanoparticles there for the desired amount of time. Due to the high local concentration of gadolinium the impact of irradiation of the neutron-capture therapy occurs very locally (radius of influence is around 100 microns from particle) but highly effectively and that preserves the healthy tissues from unwilling damage. One more potential way was found to active targeted delivery of gadolinium ions in tumors. That is immobilization of nanoparticles by adsorption on macrophages. This way may help irradiate malignant cells within ascite tumors. The composition can be stored in the laboratory for 200 days without any change in physical properties. These nanoparticles have a great affinity to gadolinium ions so have low toxic effect on living cells without irradiation.

8812-42, Session PWed

Towards an on-chip integrated NIRS photodetector front-end for real-time brain imaging

Ehsan Kamrani, Polytechnique Montréal (Canada); Frédéric Lesage, Mohamad Sawan, Ecole Polytechnique de Montréal (Canada)

Near infrared spectroreflectometry (NIRS) is a noninvasive, safe, minimally intrusive, and high temporal resolution technique with potential to be used as a portable system for real-time and long-term brain imaging, intensive care units (ICUs) and brain-computer interface (BCI) applications. This novel neuroimaging technique can non-invasively monitor the rapid changes in both fast neuronal (with ms temporal-resolution) and slow hemodynamic signals (regional cerebral blood volume and hemoglobin oxygenation). So it has potential to be applied for monitoring, evaluation and treatment of neurological diseases such as stroke and epilepsy.

However, to date the realization of this potential has not materialized with current commercial devices due to high energy consumption and size issues.

We propose in this research project a miniaturized, reconfigurable and low-noise NIRS Photodetector front-end towards an ultra-lightweight, ultra low-power wireless multichannel NIRS system for long-term monitoring applications. It includes low-voltage, low-noise, highlysensitive, and high-gain silicon avalanche photodiodes (SiAPDs), integrated with front-end circuitries for Linear and Geiger modes of operation. This fully integrated system is implemented on-chip using submicron complementary metal-oxide-semiconductor (CMOS) technology to achieve a smart-imaging sensor for several applications. Proposed SiAPDs exhibit high-avalanche gain, low-breakdown voltage and high-photon detection efficiency accompanying with low-dark count rates. The linear-mode circuitry includes three new Transimpedance amplifier (TIA) frontends with high-gain bandwidth product (GBW), low-power consumption, and ultra-low noise characteristics to be applied in continuous-wave NIRS. The TIA front-end has been designed using distributed-gain concept combined with resistive-feedback and common-gate topology. In order to operate the SiAPDs in Geiger-mode for photon-counting application, an ultra-fast Quench-Reset front-end is also implemented on-chip using standard CMOS technology. It introduces an integrated hold-off time control and on-chip counter in a small area with low-power consumption and low-noise characteristics.

8812-43, Session PWed

Low-power, high-speed, miniaturized, and controllable single-photon counting circuit dedicated to biomedical imaging applications

Ehsan Kamrani, Frédéric Lesage, Mohamad Sawan, Ecole Polytechnique de Montréal (Canada)

Single-photon detectors support a broad range of applications such as light detection and ranging (LIDAR), telecommunication systems, quantum cryptography and quantum information processing, molecular imaging and brain imaging using time correlated single-photon counting (TCSPC) and near infra-red spectroscopy (NIRS). Single-photon avalanche photodiodes (SPAD) operating at Geiger-mode, has shown the greatest potential for high-sensitivity and ultra-low intensity light detection applications due to their internal gain characteristics. An infinite selfsustaining avalanche current flows through SPAD with impact of a single photon into its surface which can be counted as a pulse at the SPAD output. In order to count the number of consequently incident photons, an external circuit called Quench-Reset is required to quench the avalanche current and then reset the SPAD bias to its initial condition after a hold-off time.

Commercially available Quench-Reset circuits suffer from high-power consumption, large-size, relatively low-speed, and high-noise which impeding developing a portable, miniaturized and low-power photon-counting system for different applications.

We have proposed and designed a miniaturized photon-counting system including a highspeed and low-power photon-counting circuit integrated with silicon CMOS avalanche photodiode (SiAPD). Integrating the SiAPD and photon-counting circuitry has reduced the afterpulsing and increased the sensitivity accompanying with significantly lower-power consumption.

Minimized controllable dead-time of the proposed system reduces the excess noise and increases the detection speed. The controllable hold-off time implemented in this circuit reduces the afterpulses and makes the system adaptable with different applications. This circuit is implemented using sub-micron standard CMOS technology and offers low-power consumption, small/controllable hold-off and quench-rest times.

8812-44, Session PWed

Plasmonic nanoantennas for monitoring single cancer cells attachment using LSPR and SERS

Alejandro Portela, Horacio Cabral, Kazunori Kataoka, Hitoshi Tabata, The Univ. of Tokyo (Japan)

This work present a biosensing method using an array of optical plasmonic nanoantennas for the analysis of cell-surface interaction through localized surface plasmon resonance (LSPR) and surface enhanced Raman spectroscopy. Calculations using different antenna length and gap size were conducted showing the tunability of the resonance peak position and the possibility to detect the changes in the refractive index produced by a single cell. The different sets of antennas with length from 40 to 100nm, gap size of 20 to 40nm were characterized by scanning electron microscopy (SEM) and their optical response registered for an array of 10 by 10 antennas separated by 1?m and for each of them individually. A bioconjugation of the gold nanoantennas was achieved using an RGD peptide that specifically bind cells containing ?v?3 receptors which are expressed on several cancer cells. The surface functionalization and cell trapping ability was verified by means of fluorescent confocal microscopy, using first a different pair of dyes for the RGD and the cell respectively. A second experiment without fluorescent dyes was conducted registering the shift on Rayleigh scattering on the arrays of nanoantennas where the cells were found. The shift on the resonance peak position was not detected in all the arrays and it showed a highest shift of 5 nm. For the single antennas analysis the shift registered reached 10 nm that is in good agreement with the numerical simulations. SERS analysis allowed verifies the binding events but also monitoring the cell attachment to the surface.

8813-1, Session 1

Theory of spin Seebeck effect in a variety of magnetic systems *(Invited Paper)*

Sadamichi Maekawa, Japan Atomic Energy Agency (Japan)

When metals and semiconductors are placed in a temperature gradient, the electric voltage is generated. This mechanism to convert heat into electricity, the so-called Seebeck effect, has attracted much attention as the mechanism for utilizing wasted heat energy [1].

Ferromagnetic insulators are good conductors of spin current, i.e., the flow of electron spins [2]. When they are placed in a temperature gradient, generated are spin current and the spin voltage [3], i.e., spin accumulation. Once the spin voltage is converted into the electric voltage by the inverse spin Hall effect in attached metal films, the electric voltage is obtained from heat energy [4-5]. This is called the spin Seebeck effect (SSE).

Here, we present the basic concept of SSE [6] and discuss about SSE in a variety of magnetic systems.

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8813-2, Session 1

Spin Seebeck effect: fundamentals and applications *(Invited Paper)*

Ken-ichi Uchida, Tohoku Univ. (Japan) and Japan Science and Technology Agency (Japan)

The spin Seebeck effect (SSE) refers to the generation of a spin voltage as a result of a temperature gradient in magnetic materials [1-5]. The SSE is of crucial importance in spintronics and spin caloritronics since it enables simple and versatile generation of a spin current from heat.

The simplest and most straightforward setup of the SSE is the longitudinal configuration [3], in which a spin current flowing parallel to a temperature gradient is measured via the inverse spin Hall effect (ISHE). The longitudinal SSE device consists of a ferromagnetic insulator (FI) covered with a paramagnetic metal (PM) film. When a temperature gradient is applied perpendicular to the FI/PM interface, an ISHE-induced voltage is generated in the PM layer.

In this talk, we report the observation of the longitudinal SSE in various FI/PM systems and provide evidence that the SSE is free from thermoelectric artifacts [5], i.e., the anomalous Nernst effect caused by extrinsic magnetic proximity [6]. Then, we discuss the SSE from an application point of view [4].

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8813-3, Session 1

Diffusion thermopower of (Ga,Mn)As/GaAs tunnel junctions *(Invited Paper)*

Charles Gould, Julius-Maximilians-Univ. Würzburg (Germany)

The issues of power consumption and heat dissipation are at the forefront of present day information technology concerns. As such, a fundamental understanding of the relationship between electrical and thermal effects is crucial to device design and operation.

One needs only consider the injection of spin polarized current into a non-magnetic semiconductor to appreciate the potential importance of these thermoelectric contributions to device behavior. Such spin injection is often detected using a four contact non-local technique, passing current between two adjacent contacts, and measuring the chemical potential difference resulting from spin accumulation at two other contacts situated at a distance from the current path. Such a measurement should yield a voltage signal which is equal but of opposite sign depending on the relative orientations of the contacts. Experimentally, this is rarely the case and the results typically include a voltage offset, which is often simply discarded as an uninteresting constant background.

This background voltage is a thermoelectric contribution. In most cases it is isotropic and adds a constant offset. As I will show in this talk, when the magnetic materials involved are crystalline with strong spin-orbit coupling, the linking of the magnetic properties to the density of states yields a spin caloritronic effect; Tunneling Anisotropic MagnetoTermopower. The thermal contribution is then far from isotropic, having a rich magnetic response. This observation may not only have interesting implications for device applications, but can also lead to misinterpretations if one fails to take it into consideration.

8813-4, Session 1

Heat transport by magnons *(Invited Paper)*

Burkard Hillebrands, Technische Univ. Kaiserslautern (Germany)

Spintronics is concerned with the development of devices which exceed the performance and energy efficiency of charge-based electronics by exploiting the electron's spin degree of freedom. Spin angular momentum, which is the information carrier in spintronics, can be transferred not only by the flow of electrons, but also by magnons: the quanta of spin waves (collective excitations of the spin lattice of a magnetic material). Magnon-based data operations have a great advantage since they are not based on the motion of any real particles like electrons in electronics - magnons are subject to dissipation to a much lesser degree than electrons. Magnon spintronics can be implemented in an electric-isolator environment (yttrium iron garnet, YIG) fully avoiding Ohmic losses. I will concentrate on the main constructing blocks of smart magnon spintronics devices: converters between the spin and charge of electrons and magnons, magnon conduits, and physical phenomena allowing information processing by magnons. The most promising convertors for the magnon spintronics are based on the spin pumping effect (which transforms spin waves into pure spin currents) and the inverse spin Hall effect (which converts spin currents into charge currents). Our study is concentrated on magnetic insulator YIG-nonmagnetic Pt structures. Magnon conduits will be discussed on the example of meso-sized YIG-based and micro-sized Permalloy-based magnonic crystals (MCs).

8813-108, Session 1

The role of phonons in the Spin Seebeck Effect *(Invited Paper)*

Joseph P. Heremans, The Ohio State Univ. (United States)

Our current understanding of the spin-Seebeck effect requires magnons in the ferromagnet to be out of thermal equilibrium, which can be done by either phonon-magnon drag or by magnon thermal conductivity itself. Our earlier experimental work on the transverse spin-Seebeck effect in GaMnAs indicated the dependence of the amplitude of the Spin Seebeck signal on the phonon mean free path, and also on phonon-electron drag. This was an indication for the presence of phonon-magnon drag. Subsequently we reported a strong spin-Seebeck-like signal in InSb in the ultraquantum regime, where the free electrons are spin polarized and where there are no magnons: here phonon-electron drag is very important. To create contrast, we will present not only these data, but also preliminary data on the spin-Seebeck effect in amorphous ferromagnets, Metglass, in which the phonons are much more localized than in the large single-crystals studied previously.

8813-5, Session 2

Stabilization and dynamics of skyrmions in nanostructures for information applications *(Invited Paper)*

Joao Sampaio, Vincent Cros, Unité Mixte de Physique CNRS/Thales (France); Stanislas Rohart, Andre Thiaville, Univ. Paris-Sud 11 (France); Albert Fert, Unité Mixte de Physique CNRS/Thales (France)

The magnetic skyrmion is a topologically stable magnetic configuration that shows many interesting particle-like behaviors, such as strong localization, attractive and repulsive interactions, and self-organization into crystalline lattices. So far observed in non-centrosymmetric bulk crystals, skyrmion lattices were recently observed in magnetic thin films, stabilized by the interfacial Dzyaloshinskii–Moriya interaction (DMI) induced by a substrate with strong spin-orbit coupling [X. Yu, PNAS, 109 8856, 2012]. Its small size, and the recently shown propagation of skyrmion lattices using small current densities [A.N. Bogdanov et al., Phys. Rev. Lett. 87 037203, 2001; S. Heinze et al., Nat. Phys. 7 713, 2011], makes it a promising basis for information-processing devices. Any practical application, however, will likely require the manipulation of isolated skyrmions in magnetic thin film nanometric structures, still to be demonstrated. We will present a comprehensive micromagnetic simulation study of isolated skyrmions in nanostructures of typical structure Pt/Co/AlOx with perpendicular magnetic anisotropy. We show that DMI stabilizes isolated hedgehog-like skyrmions in nanostructures for a large range of the DMI strength (of the order of the experimentally measured values). Furthermore, we show that several isolated skyrmions can be reliably moved along nanostripes by low current densities without changing their relative positions, even with important pinning defects, which enables encoding and transfer of information. To conclude, we have demonstrated that isolated magnetic skyrmions can be easily stabilized in magnetic 2D nanostructures as a balance between exchange, DM and magnetostatic interactions, and are promising structures for various future skyrmion-based devices.

8813-6, Session 2

Laser-induced magnetic nanostructures with tunable topological properties *(Invited Paper)*

Marco Finazzi, Politecnico di Milano (Italy); Matteo Savoini, Radboud Univ. Nijmegen (Netherlands) and Politecnico di Milano (Italy); Ali Rheza Khorsand, Radboud Univ. Nijmegen (Netherlands); Arata Tsukamoto, Nihon Univ. (Japan) and Japan Science and Technology Agency (Japan); Akyoshi Itoh, Nihon Univ. (Japan); Lamberto Duò, Politecnico di Milano (Italy); Andrei Kirilyuk, Theo Rasing, Radboud Univ. Nijmegen (Netherlands); Motohiko Ezawa, The Univ. of Tokyo (Japan)

8813-7, Session 2

Atomic-scale magnetic skyrmion lattices in ultra-thin films *(Invited Paper)*

Bertrand Dupe, Markus Hoffmann, Stefan Heinze, Christian-Albrechts-Univ. zu Kiel (Germany)

Skyrmions are topologically protected field configurations with particle-like properties that play an important role in various fields of science. They have been predicted to exist also in bulk magnets and in recent experiments it was shown that they can be induced by a magnetic field. A key ingredient for their occurrence is the Dzyaloshinskii-Moriya interaction (DMI) which was found to be strong also for magnetic nanostructures on substrates with large spin-orbit coupling [1]. In these systems the DMI stabilizes spin-spirals with a unique rotational sense propagating along one direction of the surface as observed for ultrathin films [1-3] and atomic chains [4]. Here, we go a step beyond and present an atomic-scale skyrmion lattice as the magnetic ground state of a hexagonal Fe monolayer on Ir(111) [5]. We develop a spin-model based on density functional theory that explains the interplay of Heisenberg exchange, DMI and the four-spin exchange as the microscopic origin of this intriguing magnetic state. Experiments using spin-polarized scanning tunneling microscopy confirm the skyrmion lattice which is incommensurate with the underlying atomic lattice. By growing atomic overlayers on Fe/Ir(111), e.g. Pd, Rh, or Ir, the magnetic properties of the system can be tuned which allows the observation and manipulation of individual skyrmions [6]. This work is a collaboration with G. Bihlmayer, S. Blügel, K. von Bergmann, M. Menzel, N. Romming, Ch. Hanneken, A. Kubetzka, J. Brede, and R. Wiesendanger.

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8813-8, Session 3

Entanglements in spin Seebeck effect *(Invited Paper)*

Chia-Ling Chien, Johns Hopkins Univ. (United States)

In spin Seebeck effect (SSE) [1], a metal with strong spin-orbit coupling, such as Pt, detects the pure spin current generated by a temperature gradient. SSE in transverse geometry with in-plane (ΔxT) and longitudinal geometry with out-of-plane (ΔzT) temperature gradient using Pt in contact with a ferromagnet (metal, semiconductor, or insulator) has been reported.

However, in the transverse geometry, in addition to the intended ΔxT, there exists also ΔzT in a thin magnetic film on substrate, which gives rise to the anomalous Nernst effect (ANE).

The voltages of SSE due to ΔxT and ANE due to ΔzT are additive and entangled [2]. In the longitudinal geometry with exclusive ΔzT, one encounters magnetic proximity effects in Pt that also contributes [3]. These complications prevent unequivocal establishment of SSE.

We have recently observed intrinsic SSE using longitudinal geometry in Au/YIG without magnetic proximity effects, but the signal in Au/YIG is 50 times smaller than that in Pt/YIG [4].

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8813-9, Session 3

Thermal creation of a spin current by Seebeck spin tunneling *(Invited Paper)*

Ron Jansen, National Institute of Advanced Industrial Science and Technology (Japan); J.C. Le Breton, Netherlands Foundation for Fundamental Research on Matter (FOM) (Netherlands); A.M. Deac, Helmholtz-Zentrum Dresden-Rossendorf (Germany); H. Saito, S. Yuasa, National Institute of Advanced Industrial Science and Technology (Japan)

The combination of thermoelectrics and spintronics offers unique possibilities. On the one hand, it provides a new, spin-based approach to thermoelectric power generation and cooling. On the other hand, it provides a thermal route to create and control pure spin currents without charge flow in spintronic devices that make functional use of heat. Here we describe Seebeck spin tunneling — a thermally-driven spin flow, of purely interfacial nature — generated in a tunnel contact between electrodes of different temperatures. Seebeck spin tunneling arises from the spin-dependent Seebeck coefficient of a tunnel junction and is thus the thermoelectric analog of spin-polarized tunneling.

By exploiting this in ferromagnet–oxide–silicon tunnel junctions, we observe a thermal flow of spin-angular momentum from the ferromagnet to the silicon without a charge tunnel current. This thermal spin current can be used by itself, or in combination with electrical spin injection. We describe the role of the energy-dependent tunnel spin polarization and the impedance mismatch, and compare the efficiency of electrical and thermal creation of spin. The results highlight the engineering of heat transport in spintronic devices and enable the (re-)use of heat.

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8813-10, Session 3

Planar Nernst effects and the search for thermal spin currents with in-plane thermal gradients *(Invited Paper)*

Barry L. Zink, Univ. of Denver (United States)

The generation of pure spin currents is an important requirement for future spintronic circuits. Recently some groups have reported that such a spin current can be produced simply by applying a thermal gradient to a ferromagnetic material. This effect, called the spin Seebeck effect (SSE), has generated tremendous interest

in the interaction of heat, charge and spin in ferromagnetic systems. In this talk we will present our own recent measurements of thermoelectric and thermomagnetic effects in thin film metallic ferromagnets. These are enabled by a micromachined thermal isolation platform that removes potentially confounding effects introduced by the presence of a highly thermally conductive bulk substrate. We are able to measure the thermopower (traditional Seebeck effect), thermal and electrical conductivity, and Peltier effects in addition to a variety of less widely known thermoelectric and thermomagnetic effects. One of the most interesting is the planar Nernst effect (PNE), a transverse thermopower caused by spin-dependent scattering. This PNE should therefore be present in any measurement where a thermal gradient is aligned in the plane of a magnetic metal film. Furthermore, our “zero substrate” experiment shows no signal with the symmetry of the spin Seebeck effect. This suggests that the presence of the bulk substrate is required to produce such a signal, and calls the role of a pure spin current in the effect into question. This work was performed in collaboration with A. D. Avery, D. Wesenberg, J. Underwood, and M. R. Pufall, and supported by the NSF CAREER award (DMR-0847796)

8813-11, Session 3

Spin-dependent transport of energy and heat in ferromagnetic insulators *(Invited Paper)*

Jean-Eric Wegrowe, Henri-Jean Drouhin, Ecole Polytechnique (France)

A phenomenological derivation of the transport equations for ferromagnetic energy and associated heat in ferromagnetic devices is proposed. A reduction method applied to the ferromagnetic degrees of freedom allows a two spin-channel model to be defined. The typical spintronics and spin caloritronics approach can then be generalized to ferromagnetic insulators. The coupled transport equations for non-uniform ferromagnetic excitations and heat are derived. The effect of thermal spin-injection from an insulating ferromagnet into an initially non-ferromagnetic electrode is described and discussed in terms of anomalous or planar Seebeck and Nernst effects.

8813-12, Session 4

Unconventional magnetic ordering in quantum dots *(Invited Paper)*

Igor Zutic, James Pientka, Rafal Oszwaldowski, Karel Vyborny, Jeongsu Lee, Jong Han, Univ. at Buffalo (United States); Peter Stano, Institute of Experimental Physics (Slovakia); Andre Petukhov, South Dakota School of Mines and Technology (United States)

The formation of a magnetic polaron (MP) can be viewed as a cloud of localized magnetic ion spins, aligned through an exchange interaction with a confined carrier spin and is typically considered a low-temperature phenomenon in semiconductors. However, recent experimental advances in colloidal nanocrystals and epitaxially grown quantum dots show robust signatures of MPs that can persist up to room temperature and lead to effective internal fields up to 100 tesla [1]. These highly tunable semiconductor nanostructures, allowing versatile control of the number of carriers, their spin, and the effects of quantum confinement, offer intriguing possibilities for magnetism. We suggest how magnetic ordering can be controlled even at a fixed number of carriers [2], enhanced by heating [3], and present in closed-shell systems [4]. We expect that doping quantum dots with magnetic impurities may open unexplored opportunities to study the nanoscale correlations [5]. Through Mn-carrier exchange interaction, molecular-like correlations can be enhanced, imprinted on Mn spins, and thus observed. We propose experiments to verify our predictions.

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8813-13, Session 4

Optical control of the spin of individual magnetic atoms *(Invited Paper)*

Lucien Besombes, Institut NÉEL (France)

With semiconductor quantum dots (QDs) doped with magnetic atoms, the probing of a single atomic spin in a solid state environment become possible using optical techniques. The state of a photon emitted or absorbed by a II-VI semiconductor QD containing a Mn atom is directly related to the spin state of the Mn (S=5/2). We will demonstrate that a

Mn atom or a pair of Mn atoms embedded in a QD may act as optically addressable spin based memories. We will in particular analyse how an optically induced modification of the Mn fine structure affects its spin dynamics.

8813-14, Session 4

Single spins in semiconductor quantum dot microcavities *(Invited Paper)*

Sven Höfling, Julius-Maximilians-Univ. Würzburg (Germany); Kristiaan De Greve, Peter L. McMahon, Leo Yu, David L. Press, Jason S. Pelc, Chandra M. Natarajan, Na Young Kim, Thaddeus Ladd, Eisuke Abe, Stanford Univ. (United States); Sebastian Maier, Dirk Bisping, Julius-Maximilians-Univ. Würzburg (Germany); Christian Schneider, Stanford Univ. (United States); Martin Kamp, Julius-Maximilians-Univ. Würzburg (Germany); Robert H. Hadfield, Heriot-Watt Univ. (United Kingdom); Alfred Forchel, Julius-Maximilians-Univ. Würzburg (Germany); Yoshihisa Yamamoto, Stanford Univ. (United States)

Semiconductor quantum dots can be utilized to capture single electron or hole spins and have therewith promise for various applications in fields like spintronics, spin based quantum information processing and chiral photonics. We integrate InGaAs quantum dots into semiconductor microcavities to enhance light-matter interaction for ultrafast optical manipulation and read-out. Single electron and single hole spins can be statistically or deterministically loaded into the quantum dots and coherently controlled. By applying spin echo techniques, coherence times of both spin carrier types in the microsecond-range are obtained. Within this time about 10^5 complete single qubit rotations can be performed with ultrafast optical pulses. Utilizing the type system of a single quantum-dot electron spin in a magnetic field and ultrafast non-linear frequency conversion, quantum-dot spin-photon entanglement is observed.

8813-15, Session 4

Disentangling the electron and hole g-factors of InAs/InP quantum dots *(Invited Paper)*

Joost van Bree, Andrei Y. Silov, Technische Univ. Eindhoven (Netherlands); Craig E. Pryor, Michael E. Flatté, The Univ. of Iowa (United States); Paul M. Koenraad, Technische Univ. Eindhoven (Netherlands)

A single spin in a quantum dot provides a model system for the observation and manipulation of an individual quantum system, and has been proposed as a qubit for usage in quantum information technology. The magnetic moment and Zeeman energy splitting of such a single spin are controlled by the g-tensor, whose value in the solid state differs from the bare electron g-factor of ~2 due to strong spin-orbit interaction. Therefore control over the g-tensor provides an effective spin-manipulation method, and a thorough understanding of the nature of the g-tensor is desired.

We will present a detailed magneto-optical study on self-assembled InAs/InP quantum dots. By applying a magnetic field in various directions, we have been able to separate the electron and hole g-factors of a single quantum dot in different spatial directions. We observe a strong size dependence of the g-factor, which can be explained in terms of quenching of the envelope orbital momentum by spatial confinement. This size dependence of the g-factors is confirmed by k.p-calculations. Interestingly, by tuning the height of the quantum dot it is possible to change the sign of either the electron or the hole g-factor or choose it to be close to zero. Moreover, we observe that the g-factor is sensitive to its electrostatic environment. This opens up a route to actively control the spin state: one can flip the spin of a quantum dot having a g-factor close to zero, by applying an electric field across the quantum dot which changes its sign.

8813-16, Session 4

Magnetism of magnetic ion doped semiconductor nanocrystals *(Invited Paper)*

Shou-Jyun Zou, National Chiao Tung University (Taiwan); Shun-Jen Cheng, National Chiao Tung Univ. (Taiwan)

Magnetic ion-doped semiconductor nanocrystals (NCs) have recently drawn a great deal of interest because of the intriguing physical properties and the potential application in spintronics and magneto-electronics. Rich physical phenomena, such as giant Zeeman splitting [1], spontaneous magnetization [2], complex excitonic fine structures [3] and quantum-size induced paramagnetism[4,5], have been observed in self-assembled quantum dots or colloidal nanocrystals doped with magnetic ions, typically Mn2+.

We report on our recent theoretical studies of magnetic CdSe NCs and the comparison with existing experiments. [5-7] The exact diagonalization (ED) technique is emplyed to compute the electronic and magnetic properties of the spherical NCs with controlled number of magnetic ions Mn2+ and electrons. The ED approach, beyond the widely used mean field theory for magnetic semiconductor bulks and thin films, takes fully into account the electron-electron, ferromagnetic (FM) electron-Mn and antiferromagnetic (AFM) Mn-Mn interactions. For more physical analysis, a spin theory based on a constant interaction model is developed for dealing with magnetic semiconductor NCs with arbitrary number of magnetic ions. The numerical results are physically elucidated by formailsms yielded by analysis whenever it is possible.

As main results, ferromagnetic magnetic polarons (MPs) with fully polarized Mn spins are shown to be stably formed in small magnetic NCs due to the strong dot confinements. For large NCs, the magnetic polarons might exhibit various magnetic phases, from ferromagnetism (FM) to anti-ferromagnetism (AF), depending on the spatial distribution of Mn ion impurities. Another remarkable revealed feature is the predicted existence of magnetic anisotropies (MAs) in symmetric magnetic NCs. The physical origins of the MAs are associated with the scatterings of electron carriers to magnetic ions and the resulting quenching of orbital magnetic moments. Experimentally, pronounced paramagnetism of Mn-doped CdSe NCs was observed in the presence of magnetic fields. Surprisingly the paramagnetism lasts over a wide range of magnetic field B up to 6 Tesla, far above the B-range given by Curie's law. The uncommon paramagnetic feature is regarded as a direct signature of anti-ferromagnetic interaction between Mn ions according to our theoretical studies. In summary, our ED studies provide a theoretical description for the electronic and magnetic properties of magnetic ion doped NCs and suggest the controllability of magnetism in the magnetic semiconductor nanostructures.

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8813-17, Session 5

Generation and manipulation of spin wave by spatially shaped light spot *(Invited Paper)*

Takuya Satoh, The Univ. of Tokyo (Japan)

In a magnetically ordered material, the interaction of spins leads to a propagating wave of spin precessional motion. This 'spin wave' shows promise as a new kind of information carrier even in an insulator. This

phenomenon has attracted much attention in the field of 'magnonics,' that is, using the spin wave that is generated, controlled, and detected as an information carrier. One critical challenge, however, is to establish a suitable control technology for the propagation of spin waves. Here we propose a promising technique that uses a spatially shaped light pulse with circular polarization. Focusing this light pulse on a magnet generates spin waves within the light spot via the inverse Faraday effect. Moreover, the wave number distribution of the spin waves is determined by the spatial intensity distribution of the light spot. We demonstrated the principle of this technique experimentally and numerically. We successfully controlled the direction of the energy flow by shaping the light spot into an ellipse with its major axis parallel or perpendicular to the magnetic field. Our findings will open up the possibility of fast and arbitrary synthesis of spin wave patterns by using a more sophisticated light shaping technique, such as use of a computer-generated hologram.

8813-18, Session 5

Thermal effects in the planar approximation for spin torque dynamics *(Invited Paper)*

Yaroslaw Bazaliy, Univ. of South Carolina (United States)

Thermal effects play an important role in the current-induced magnetization dynamics experiments performed at room temperature. Temperature fluctuations can be described by a two-dimensional diffusion equation for the magnetization direction. It is also known that a deterministic description of spin torque devices with strong easy plane magnet can be reduced to a simplified one-dimensional effective equation that only takes into account small deviations of magnetization from the easy plane. Here we study thermal effects in such strong easy plane devices and develop a one-dimensional probabilistic description of their behavior.

8813-19, Session 6

Topological insulators from the view point of chemistry *(Invited Paper)*

Claudia Felser, Max-Planck-Institut für Chemische Physik Fester Stoffe (Germany)

Topological insulators are a hot topic in condensed matter physics. The excitement in the physics community is comparable with the excitement when a new superconductor is discovered. Many Heusler compounds with C1b structure are ternary semiconductors that are structurally and electronically related to the binary semiconductors. The diversity of Heusler materials opens wide possibilities for tuning the bandgap and setting the desired band inversion by choosing compounds with appropriate hybridization strength (by the lattice parameter) and magnitude of spin-orbit coupling (SOC, by the atomic charge). Based on first-principle calculations we demonstrate that around 50 Heusler compounds show band inversion similar to that of HgTe [1]. The topological state in these zero-gap semiconductors can be created by applying strain or by designing an appropriate quantum well structure, similar to the case of HgTe. Many of these ternary zero-gap semiconductors (LnAuPb, LnPdBi, LnPtSb and LnPtBi) contain the rare-earth element Ln, which can realize additional properties ranging from superconductivity (for example LaPtBi) to magnetism (for example GdPtBi) and heavy fermion behaviour (for example YbPtBi). These properties can open new research directions in realizing the quantized anomalous Hall effect and topological superconductors. C1b Heusler compounds have been grown as single crystals and as thin films. The control of the defects, the charge carriers and mobilties will be optimized and quantum well structures will be grown. The combination of a piezoelectric Heusler compounds and compounds at the borderline between trivial and topological insulators offers the possibility of a switchable device. It is also possible to design new topological insulators with strong correlations. In AmN and PuTe a band gap is opened by correlation effects. In a family of semiconductors with the simple NaCl structure band gaps up to 0.4 eV were found [2]. This is not so surprising since the SOC should be large in Actinides. Heusler compounds are similar to a stuffed diamond, correspondingly, it should be possible to find the "high Z"' equivalent of graphene in a graphite-like structure or in other related structure types with 18 valence electrons and with inverted bands [3]. Indeed the ternary compounds, such as LiAuSe and KHgSb with a honeycomb structure of their Au-Se and Hg-Sb layers feature band inversion very similar to HgTe which is a strong precondition for existence of the topological surface states [4,5]. LiAuSe is a strong TI, whereas KHgSb a weak TI. We will discuss the necessary and sufficient conditions for new TI materials, based in symmetry and bonding arguments [3].

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8813-20, Session 6

Magnetospectroscopy of HgTe-based topological insulators *(Invited Paper)*

Frédéric Teppe, Univ. Montpellier 2 (France); Wojciech Knap, Univ. Montpellier 2 (France) and Ctr. National de la Recherche Scientifique (France); Maksim Zholudev, Christophe Consejo, Nina Diakonova, Dominique Coquillat, Dmitro B. But, Univ. Montpellier 2 (France)

Recently, a new class of topological insulators was experimentally demonstrated in materials with band inversion due to strong spin-orbit coupling [B. Andrei Bernevig, et al., Science 314, 1757 (2006); M.Z. Hasan and C.L. Kane, Rev. of Modern Physics 82, 3045 (2010)]. Indeed, HgTe/CdxHg1-xTe quantum wells can change to topological insulator phase from conventional insulator phase when the thickness of the quantum well is varied to the critical thickness dc = 6.3 nm. In this work, we study a set of four samples of different quantum well width by magnetospectroscopy from below to above the critical thickness dc. In quantizing magnetic fields up to 16 T, both intraband and interband transitions have been observed. For the widest QW we confirm the observation of the crossing of the zero-mode Landau due to the breaking of time-reversal symmetry. In both non-inverted quantum wells close to the critical thickness, we report unambiguously on the square root dependence of the transition energy on the magnetic field, as expected in the single-particle model of massless Dirac fermions.

8813-21, Session 6

Ambipolar Rashba effect in the semiconductor compounds BiTeX *(Invited Paper)*

Luca Moreschini, Lawrence Berkeley National Lab. (United States); Alberto Crepaldi, Gabriel Autes, Helmut Berger, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Aaron Bostwick, Eli Rotenberg, Lawrence Berkeley National Lab. (United States); Oleg Yazyez, Marco Grioni, Ecole Polytechnique

Fédérale de Lausanne (Switzerland)

The relativistic spin-orbit interaction can lift the usual electron spin degeneracy only when space inversion symmetry is broken. Such symmetry breaking can be provided either by the non-centrosymmetric structure of the bulk crystal, or at surfaces and interfaces. Both cases have attracted the attention of condensed matter physicists in the last years because of obvious implications for spin-dependent transport. In the former category, the case of the semiconductor BiTeI has very recently been object of special interest. With its polar stacking of atomic layers, it present a similar structure to the class of Bi-based topological insulators, and has been shown to present clear spin-split bands both in the valence and conduction electronic states. We have studied by angle-resolved photoemission (ARPES) the band structure of the BiTeX (X=I, Br, Cl) class of compounds, and we have shown that acting on the surface termination the chemical potential can be controllably placed in either of the bands. Therefore, the BiTeX materials present two key ingredients for spin-based electronics: a large spin-orbit splitting of the transport electrons and ambipolar conduction.

8813-22, Session 7

Fine structure of band-edge excitons in PbSe nanocrystals and nanorods *(Invited Paper)*

Joseph G. Tischler, Evan R. Glaser, Edward E. Foos, Diogenes Placencia, Woojun Yoon, Janice E. Boercker, Alexander L. Efros, U.S. Naval Research Lab. (United States)

Lead chalcogenides are unusual semiconductors with a direct gap at the L points of the Brillouin zone. The 4-fold degeneracy of the L points implies 4-fold degeneracy of the 1S ground states of electrons and holes. In nanocrystals (NCs) this degeneracy leads to fine structure in the spectrum of band-edge excitons that are controversial.

The fine structure of these states is a complicated function of the intervalley interaction, the electron-hole exchange interaction, and deviations of the NC shape from spherical symmetry such as in NRs. The high degree of degeneracy of the exciton states in these NCs makes fluorescence line-narrowing experiments inefficient for studying their fine structure and highlights the need for alternative approaches.

Here we study the fine structure of band-edge excitons in PbSe nanocrystals and nanorods using two magneto-optical methods: circularly polarized magneto-photoluminescence and optically detected magnetic resonance. Our data are well described by the standard singlet-triplet model of exciton photoluminescence from non-degenerate electrons and holes. This suggests that intervalley splitting is much larger than electron-hole exchange in PbSe NCs. Our magneto-optical data directly give the electron and hole g-factors as well as the electron-hole exchange interaction. We find that the electron and hole g-factors are both positive, with ge slightly larger than gh. We also find that at low temperature the emission comes from the triplet dark state (phosphorescence), because of the large exchange energy (several tens to hundreds of meV). Finally, we show that the exchange energy is inversely proportional to the NC volume.

8813-23, Session 7

A new twist on organic spintronics: controlling transport and electroluminescence in organic sandwich devices using fringe fields from ferromagnetic films *(Invited Paper)*

Markus Wohlgenannt, The Univ. of Iowa (United States)

Organic spintronics is concerned with the study of spin-injection and magnetic-field dependent transport phenomena in organic semiconductors. In addition to spin-valve effects, there exists a large room-temperature magnetoresistive effect in organic devices made entirely from non-magnetic materials, the so-called organic magnetoresistive (OMAR) effect, which has no analogue in inorganic spintronics. OMAR is known to be caused by the variation from hopping site to hopping site of the nuclear hyperfine field, and this can dramatically affect the electronic hopping transport in organics. We demonstrate a third, new method of controlling the electrical conductivity and electroluminescence of an organic film at room temperature, using the spatially-varying magnetic fringe fields of a magnetically-unsaturated ferromagnet. Surprisingly these inhomogeneous fringe fields vary over length scales roughly two orders of magnitude larger than the hopping length in the organic materials, and the theoretical explanation of the effect is more challenging than hyperfine-related models of magnetotransport. We explain the experimental magnetoresistance traces using a model based on differential electron spin precession in magnetic field gradients. Our devices, which do not rely on spin injection, tunneling anisotropic magnetoresistance or spin-valve behavior, may provide a simple approach to integrating magnetic metals and organics for hybrid spintronic devices. These devices may find application as high-voltage readouts of the magnetic state of low-impedance ferromagnetic films.

8813-24, Session 7

Exchange interaction of transition metal spin centers in diamond *(Invited Paper)*

Victoria R. Kortan, Cuneyt Sahin, Michael E. Flatté, The Univ. of Iowa (United States)

Advances in single-ion implantation as well as electronic and optical spectroscopy have permitted direct observation of the exchange interaction between two dopant spins in a semiconductor[1,2], which is accurately described by tight-binding models of the semiconducting host[2,3]. These advances suggest controllable fabrication and utilization of few-dopant structures to explore fundamental properties and for applications[4]. Transition metal substitutional dopants in tetrahedrally-bonded semiconductors are good candidates for controllable spin manipulation and spin-spin interaction because they offer both highly-localized and more extended spin-polarized states. For example, both the Ni and Cr dopants have spin-1 ground states in diamond, but the extent of wavefunction localization is very different[5]. We calculate the exchange interaction between pairs of transition metal spin centers and between two NV centers in diamond as a function of pair separation using the technique of Ref. 3, but with an spds* tight-binding model. We find strong exchange interactions between pairs of transition metal dopants as well as between two NV centers. This work was supported by an AFOSR MURI. [1] Semiconductor Spintronics and Quantum Computation, ed D.D. Awschalom, N. Samarth & D. Loss (Springer Verlag, Heidelberg, 2002). [2] D. Kitchen et al., Nature 442, 436 (2006). [3] J.-M. Tang & M.E. Flatté, Phys. Rev. Lett. 92, 047201 (2004). [4] P. Koenraad & M.E. Flatté, Nat. Mat. 10, 91 (2011). [5] T. Chanier, et. al., Phys. Rev. B 86, 085203 (2012).

8813-25, Session 7

Quantum dynamics and control of spins in diamond *(Invited Paper)*

Viatcheslav Dobrovitski, Ames Lab. (United States)

Understanding and controlling quantum spins in solids is an exciting scientific endeavor. Besides fundamental interest in non-equilibrium quantum many-spin dynamics, this research is important for applications ranging from nanosciences and spintronics, to advanced sensing and quantum information science.

The nitrogen-vacancy (NV) centers in diamond have emerged as a promising platform for prospective solid-state quantum spin technologies. I will present our recent work on investigating and controlling the quantum spin dynamics of individual and coupled electronic and nuclear spins in diamond. Advanced approaches for quantum spin control, based on the pulse dynamical decoupling, enable protection of quantum coherence of the NV center's spin [1] from its solid-state environment [2]. Furthermore, the decoherence-protected quantum spin dynamics can be extended to the case of coupled spins, thus enabling high-fidelity quantum gates on two spin qubits in diamond, and the resulting first implementation of the quantum search algorithm with solid-state spins [3]. Further extending this approach to the few-spin case, we have demonstrated an extremely sensitive nanoscale tomography with nanometer resolution and sensitivity to a single nuclear spin [4]. Finally, I will discuss how these advances can make possible multi-qubit quantum registers for the small-scale quantum information processing in diamond.

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8813-26, Session 7

Nonlocal, local, and extraction spin valves based on ferromagnet/semiconductor hybrid structures consisting of the Heusler alloy Co2FeSi on GaAs *(Invited Paper)*

Manfred Ramsteiner, Yori Manzke, Pawel Bruski, Rouin Farshchi, Jens Herfort, Paul-Drude-Institut für Festkörperelektronik (Germany)

Lateral transport structures which take advantage of a shared interface of the semiconductor (SC) with a ferromagnetic metal (FM) are important building blocks for spintronic applications. From the materials point of view the hybrid system Co2FeSi on GaAs has been proven to be very promising particularly because of the high efficiency of electrical spin-injection.

We demonstrate nonlocal, local and extraction spin-valve structures consisting of Co2FeSi stripes on an n-type GaAs transport channel. In extraction spin valves (ESV), we utilize the accumulation of spin-polarized electrons in the SC that results from spin reflection of electrons drifting towards an SC/FM interface. In this presentation we compare the operation of nonlocal, local and extraction spin valves and explain the observed peculiarities with the specific bandstructure of fully and partially ordered Co2FeSi.

Finally, we elucidate the extension of the ESV concept to a functional spintronic circuit that comprises multiple extraction events. Such a multiple extraction spin valve (MESV) acts as a configurable current divider in which the accumulation of spin-polarized electrons in the SC channel drifts toward consecutive ferromagnetic stripes. As a result, a single electrical output corresponds to a particular magnetization configuration of the entire stripe array. We discuss potential implementations of this concept for spintronic memory and magneto-logic circuits and for sources of highly spin-polarized drift currents.

8813-27, Session 7

Light-matter-spin interactions in colloidal quantum structures *(Invited Paper)*

Min Ouyang, Univ. of Maryland, College Park (United States)

Semiconductor based colloidal quantum structures represent attractive systems to study various fundamental physics and applications at the nanoscale, including scalable solid-state implementations of quantum information pro- cessing by using spins of electrons and excitons as qubits. In this talk I will discuss a few recent progresses from my group on the topic of spin dynamics and spin manipulation in colloidal nanostructures. I will start with general spin coherence dynamics in pure semiconductor quantum dots probed by ultrafast laser spectroscopy, followed by its hydrostatic pressure effect and novel plasmon enhanced spin manipulation and spin echo enabled by a unique metal-semiconductor colloidal hybrid quantum structures.

8813-28, Session 8

Andreev nanoprobe of half metals and topological insulators using d-wave superconductors *(Invited Paper)*

John Y. T. Wei, Univ. of Toronto (Canada)

Andreev reflection (AR) spectroscopy is a powerful technique for probing the electron spin polarization of ferromagnetic materials [1]. This technique exploits the fundamental spin correlation of the AR process, and has been implemented using various contact geometries and s-wave superconductors as counterlectrode. In this talk, I will survey recent developments in this field, particularly the use of high-Tc cuprate tips as d-wave superconducting counterelectrode. I will discuss the inherent advantages of d-wave AR spectroscopy, namely high junction impedance which eliminates Joule heating, and small junction size which enables sub-domain resolution. These concepts have been realized using YBa2Cu3O7 tips on CrO2 films in a point contact geometry, demonstrating spin-polarized measurement at ~ 10nm length scales [2]. Finally, I will preview the extension of d-wave AR spectroscopy to probing the spin correlations of topological insulators, as well as the realization of spin-sensitive Andreev nanoprobe above 77K.

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8813-29, Session 8

First principles modeling of electron scattering in topological insulators *(Invited Paper)*

Hong Guo, McGill Univ. (Canada); Jian Wang, Lei Zhang, The Univ. of Hong Kong (China); Xuefeng Wang, Suzhou Univ. (China); Yibin Hu, Mcgill Univ. (Canada); Leo Liu, Nanoacademic Technologies Inc. (Canada); Yonghong Zhao, Sichuan Normal Univ. (China)

Topological insulators (TI) are materials having an energy band gap in the bulk and conducting helical electronic states on the surface which have the peculiar property that the direction of the electron spin is locked to its momentum. The helical states are protected by time reversal symmetry hence robust against static disorder scattering, a property that can be exploited for spintronics. The physics of TI is induced by strong spin-orbit interaction. We have analyzed the quantum transport properties of TI device structures from atomistic first principles. On the technical side, we have carried out density functional theory (DFT) analysis within the Keldysh nonequilibrium Green's function (NEGF) formalism where the device Hamiltonian and quantum transport properties of the open two-probe transport junction structures were calculated self-consistently including the spin-orbit contributions. In the NEGF-DFT formalism, the density matrix is calculated by NEGF under external bias voltage, and the nonequilibrium density matrix is used to construct the self-consistent field (SCF) that determines the Hamiltonian of the system. At equilibrium, the SCF reduces to the DFT potential. To deal with the spin-orbit physics in TI accurately, triple-zeta double-polarization atomic orbital basis functions are used to expand the physical quantities. In this talk, I will present NEGF-DFT first principles calculations of the helical state induced by spin-orbit interactions on TI surfaces, the spin-texture, the spatial distribution of the spin states, and the electron scattering by static potential perturbations. We establish a quantitative picture on how strong a bulk perturbation could derail the helical surface spin states. Three dimensional TI material Bi2Se3 will be focused. I will also briefly report a mesoscopic phenomenon in TI nanowires having a finite cross section, where a stripe state appears to form on the surfaces due to a strong anisotropy of the material. It was found numerically that in the diffusive regime the average conductance of stripe states is quantized with fractional values.

8813-30, Session 8

Spin-orbit interaction at surfaces: Rashba-type spin structures in the unoccupied bands *(Invited Paper)*

Markus Donath, Sebastian D. Stolwijk, Sune N. Wissing, Anna Zumbülte, Anke B. Schmidt, Peter Krüger, Westfälische Wilhelms-Univ. Münster (Germany); Kazuyuki Sakamoto, Chiba Univ. (Japan)

Spin-orbit-induced spin splittings in the surface electronic structure of heavy elements and topological insulators are a hot topic of today's research in condensed matter physics. The interest is guided by possible applications of these materials in spintronic devices, in which the electron spin is used as an information carrier. While the occupied bands are thoroughly investigated by spin- and angle-resolved photoemission, there is basically a blank area on the E(k||) map beyond the Fermi level.

We present spin- and angle-resolved inverse-photoemission results on the unoccupied surface bands of selected Rashba systems. A home-made rotatable spin-polarized electron source allows the investigation of k-dependent spin structures.

(i) The Au(111) surface with its sp-derived surface state serves as a prototype system for probing Rashba-type spin splittings with inverse photoemission. (ii) Tl/Si(111)-(1x1) is an outstanding example for a system having surface states with peculiar spin-orbit-induced spin structures. We observe an unoccupied surface state with k-dependent rotation of the spin polarization from in-plane to out-of-plane upon approaching the K point. Here, the two spin components are split in energy by more than 0.5 eV, which leads to almost complete spin polarization at the Fermi level. (iii) Among the surface alloys with heavy elements on noble metals, the √3x√3R30° Bi/Ag(111) ordered surface alloy stands out as the system with the largest Rashba parameters. Our study unveils the E(k||) dispersion of several unoccupied surface bands with distinct spin polarization.

8813-31, Session 8

Splitting electrons with dirt: Majorana fermions from scattering *(Invited Paper)*

Inanc Adagideli, Sabanci Univ. (Turkey)

We focus on inducing topological state from regular, or irregular scattering in (i) p-wave superconducting and (ii) proximity coupled Rashba wires [1]. We find that while disorder is detrimental to topological state in p-wave wires, we find that it can induce topological state in Rashba wires contrary to common expectations. We find that the total phase space area of the topological state is conserved for long disordered wires, and can be even increased in an appropriately engineered superlattice potential. Finally we relate the topological charge to normal state conductance and spin conductance. [1] I. Adagideli, M. Wimmer, and A. Teker, arXiv:1302.2612

8813-32, Session 8

A fundamental view on spintronics: from Rashba-type spin-splitting to topological insulators *(Invited Paper)*

Christian R. Ast, Max-Planck-Institut für Festkörperforschung (Germany)

The Rashba-Bychkov (RB) model has been remarkably successful in describing the spin splitting of two-dimensional (2D) electron systems with a structural inversion asymmetry (SIA), which makes it one of the key mechanisms in the emerging field of spintronics for manipulating the electron spin without the use of magnetic fields. Using angular resolved photoemission spectroscopy as well as scanning tunneling microscopy/spectroscopy, we were able to show that the Bi/Ag(111) surface alloy is a representative of a new class of materials, which exhibits a particularly large Rashba-type spin-splitting. The fact that only a fraction of the atoms in a surface alloy exhibit a large atomic spin-orbit interaction question the dominant role of the atomic spin-orbit coupling and point towards a strong structural influence in the spin-splitting mechanism. We have transferred this concept onto a semiconducting surface, where we also identified a large spin-splitting in Bi/Si(111). The recently discovered topological insulators (TI) can be regarded as the topologically non-trivial counterpart of the Rashba-type spin-splitting. Here as well, 3D TIs exhibit a robust surface state with unique properties, such as forbidden back scattering. Using Bi2Se3 as a model system, we discuss the effects of exposure to ambient conditions and the environmental robustness; an issue that needs to be clarified if 3D TIs are to be used in spintronics devices.

8813-33, Session 9

Expanded horizons for generating and exploring optical angular momentum in vortex structures *(Keynote Presentation)*

David L. Andrews, Univ. of East Anglia Norwich (United Kingdom)

It is well known that spin offers a useful extension to the information capacity of nanometer-scale electronic devices, and that it is possible for spin transfer to effect high fidelity communication between component units such as quantum dots. In the field of spin optics, standard methods provide for two independent degrees of freedom to be communicated by photon polarization: circular states of opposing handedness are the most obvious candidates, although any two states that correspond to diametrically opposite positions on the Poincaré sphere provide a suitable basis. However, various forms of complex light with structured wave-fronts or vector polarization now offer additional degrees of freedom, enabling individual photons to convey a far greater information content than was previously thought possible. There is particular interest in Laguerre-Gaussian modes, whose helically twisted wave-front is associated with orbital angular momentum, in addition to any spin due to polarization. Experiments demonstrate that single photons carry the entire spatial helical-mode information. Moreover, twisted optical modes provide for the generation of surface plasmon optical vortices. As the field continues to grow and the technical difficulties are overcome, it has now been recognized that electron beams have a similar capacity for vortex propagation, suggesting new possibilities to resolve high density information from suitable structures.

8813-34, Session 9

Spin-orbit interaction in optical singularimetry *(Invited Paper)*

Joerg B. Goette, Max-Planck-Institut für Physik komplexer Systeme (Germany)

Singularimetry is a new and elegant optical measurement technique which utilises the position of vortices in the spin and orbital currents to gather information about material properties or dynamic processes on an interface [1]. It is based on the fact that a vortex beam [2] upon reflection from or transmission through an interface experiences a change in its topology - a higher charge vortex breaks up into a constellation of unit vortices. The position of these vortices within the light beam depend on higher order terms of the optical spin-orbit coupling. A measurement of the vortex position can therefore reveal information about topological aberrations and the structure of interface.

The scheme makes use of a pre- and postselection of the polarization (or spin) of the light, and is analogous to a quantum weak measurement [3]. Varying the input and output spin of the light changes the observable vortex constellation, and probes all elements of the a scattering matrix, which mediates the light-matter interaction. Increasing the vortex charge probes higher order terms in systematic expansion of the scattering matrix in terms of a spin-orbit coupling parameter. As the scheme is based on the topology of wave fields it is not just restricted to optical beams.

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8813-35, Session 9

Quantum information processing with spin-orbit laser modes *(Invited Paper)*

Antonio Z. Khoury, Carlos Eduardo R. Souza, Allan R. Vieira, Univ. Federal Fluminense (Brazil); Malena O. Hor-Meyll, UFRJ (Brazil)

Optical beams carrying orbital angular momentum have attracted considerable interest both in quantum optics and quantum information. These beams are optical vortices produced by holographic techniques and astigmatic mode converters. Their application to quantum information tasks ranges from implementation of conditional quantum gates to quantum criptography. Combination of orbital and spin angular momenta allows one to encode and operate a pair of independent qubits on a single photon. These degrees of freedom can be entangled to each other (internal entanglement) as well as to those of other photons (hybrid entanglement), giving rise to new implementations of quantum communication protocols.

While the photon spin can be easily operated with polarization devices (wave plates and polarizing beam splitters), the orbital degree of freedom requires a more involved approach. We shall discuss some simple setups used to operate and select paraxial modes carrying orbital angular momentum. We developed a single lens design for an astigmatic mode converter and implemented a controlled-not gate based on a Michelson interferometer. We also used a modified Sagnac interferometer to sort the spin-orbit modes according to their parity. The Sagnac geometry benefits from phase stability and allows for independent manipulation of the interfering beams.

8813-36, Session 10

Beaming and steering of photons with spin and orbital angular momentum using spiral plasmonic antenna *(Invited Paper)*

Qiwen Zhan, Univ. of Dayton (United States)

In this talk, I will present some of our latest works on the beaming and steering of photons with angular momentum using spiral plasmonic antennas. Through coupling quantum dot nano-emitters to a spiral plasmonic antenna, highly directive nano-scale photon sources that emit photons with spin and orbital angular momentum can be realized. Both analytical and numerical models indicate that the beamed photons can be imprinted with desired photonic spin angular momentum and orbital angular momentum information simultaneously via the interactions between the nano-emitters and the plasmonic spiral antenna. These theoretical predictions are confirmed by results obtained from carefully designed experiments. Furthermore, the feasibility of controlling the emission direction of the nano-scale spin photon source is demonstrated by both numerical simulation and experimental results. The beaming direction can be steered through introducing a displacement to the emitters away from the geometrical center of the spiral antenna. A steerable nanoscale spin photon source may find important applications in single molecule sensing, quantum optical information processing and integrated photonic circuits.

8813-37, Session 10

Structured light in nanostructures *(Invited Paper)*

Natalia M. Litchinitser, Jingbo Sun, Mikhail I. Shalaev, Jinwei Zeng, Alexander N. Cartwright, Univ. at Buffalo (United States)

We discuss fundamental optical phenomena at the interface of singular optics and nanostructured optical materials, including theoretical and experimental studies of linear and nonlinear light-matter interactions of vector and singular optical beams in optical metamaterials. Understanding the physics of the interaction of complex beams with nanostructured “engineered” media is likely to bring new dimensions to the science and applications of complex light, including novel regimes of spin-orbit interaction, extraordinary possibilities for dispersion engineering, and novel possibilities for nonlinear singular optics.

We report theoretical and experimental studies of linear and nonlinear interactions of complex light beams with orbital angular momentum with fiber-based magnetic and negative-index metamaterials. In particular, our studies show that magnetic metamaterials can be used to manipulate complex polarization states, while negative index metamaterials can be used to manipulate the phase front of singular beams. We also predict that backward phase-matched process in negative index metamaterials with quadratic nonlinearity results in generation of backward propagating vortex beam with simultaneously doubled frequency and orbital angular momentum and reversed rotation direction of the wavefront. Finally, we discuss structured light propagation in indefinite optical metamaterials and propose several novel functionalities enabled by these strongly anisotropic structures, including beam intensity and wavefront shaping as well as transformations of orbital angular momentum.

These studies could find applications for multidimensional information encoding, secure communications, and quantum cryptography as both spin and orbital angular momentum could be used to encode information; dispersion engineering for spontaneous parametric down-conversion; and on-chip optoelectronic signal processing.

8813-38, Session 10

The Lorentz force law and its connections to hidden momentum, the Einstein-Laub force, and the Aharonov-Casher effect *(Invited Paper)*

Masud Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States)

The Lorentz force of classical electrodynamics, when applied to magnetic materials, gives rise to hidden energy and hidden momentum. Removing the contributions of hidden entities from the Poynting vector, from the electromagnetic momentum density, and from the Lorentz force and torque densities simplifies the equations of the classical theory. In particular, the reduced expression of the electromagnetic force-density becomes very similar (but not identical) to the Einstein-Laub expression for the force exerted by electric and magnetic fields on a distribution of charge, current, polarization and magnetization. Examples reveal the similarities and differences among various equations that describe the force and torque exerted by electromagnetic fields on material media. An example of the simplifications afforded by the Einstein-Laub formula is provided by a magnetic dipole moving in a static electric field and exhibiting the Aharonov-Casher effect.

8813-39, Session 10

Spinoptical metamaterials: spin-controlled photonics based on symmetry violation *(Invited Paper)*

Nir Shitrit, Igor Yulevich, Elhanan Maguid, Dror Ozeri, Dekel

Veksler, Vladimir Kleiner, Erez Hasman, Technion-Israel Institute of Technology (Israel)

Metamaterials are artificial matter structured on a size scale smaller than the wavelength of external stimuli enabling a custom-tailored electromagnetic response of the medium and thus leading to state-of-the-art functionalities. Alongside, spinoptics provides an alternative route to control light, whereby the photon spin – circular polarization helicity – is utilized as an additional degree of freedom in nano-optics, and consequently, paving the way for optical spin degeneracy removal phenomena owing to a geometric gradient in a structured matter. Specifically, spinoptics enables one to engineer a metamaterial dispersion in a spin-dependent manner as in the Rashba effect in spintronics, which is a manifestation of the spin-orbit interaction under broken inversion symmetry, i.e., the inversion transformation does not preserve the structure.

Here, we report on a spinoptical metamaterial manifested by a spin-controlled dispersion owing to the optical Rashba effect. The observed spin-split dispersion of spontaneous emission is attributed to the optical spin-orbit interaction under spatial inversion asymmetry in anisotropic inhomogeneous structured matter. We obtain an inversion asymmetric metasurface by modeling the uniform and the staggered chirality spin-folding modes of the frustrated kagomé antiferromagnet in artificial structures with anisotropic antenna configurations. The spin-dependent dispersion of a spinoptical metamaterial is governed by a momentum selection rule, generated by the representation theory considering the structure symmetry restrictions, highlighting the combined contributions of the structural and orientational lattices. This new type of metamaterial is a starting point for integrated spintronic-spinoptical applications based on design of the metasurface symmetry properties via anisotropic nanoantennas with space-variant orientation.

8813-40, Session 11

Electrical detection of three-terminal Hanle-effect signals in Si across Schottky tunnel barriers *(Invited Paper)*

Kohei Hamaya, Kyushu Univ. (Japan); Yuichiro Ando, Osaka Univ. (Japan)

Here we show some interesting phenomena in spin accumulation signals, detected by the three-terminal Hanle-effect measurements, in Si-based lateral devices. Using a delta-doping approach, we fabricated Schottky tunnel barriers between CoFe and Si. Thus, our devices have no insulating tunnel barriers at the contacts. Across the Schottky tunnel barriers, we can detect spin accumulation in nondegenerated Si channels [1-3]. First, the electrical detection of the spin-accumulation signals at room temperature was achieved in a Si-MOSFET structure [1]. Interestingly, the magnitude of the spin signals was able to be modulated by the application of gate voltage. Next, the influences of the presence of the localized states at the CoFe/Si interface and of magnetic domain structures in the CoFe contact on the spin-accumulation signals will be discussed [2,3]. Finally, the effect of the replacement of the CoFe contact with Heusler-alloy contacts on the spin signals will be discussed [4].

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8813-41, Session 11

Electrical spin injection into silicon and the role of Schottky barrier *(Invited Paper)*

Saroj P. Dash, Chalmers Univ. of Technology (Sweden)

Electrical creation of spin polarization in semiconductors and understanding the process of spin injection and detection are the main challenges in spintronics.

Electrical spin injection and detection has been demonstrated in silicon at room temperature for the first time by Dash et al. [1, 2]. Several control experiments also have proven unambiguously that the large room temperature spin signal originates from spin-polarized tunneling and spin accumulation in the Si bands [3]. The Schottky barrier profile at the interface mainly controls the spin transport process. Here we will present the role of Schottky barrier on the spin injection and detection in silicon. Using a very narrow Schottky barrier and SiO2 tunnel barrier, we demonstrate a giant spin accumulation in highly doped silicon at room temperature. With an increase in Schottky barrier width we observe a sign-reversal of the Hanle spin signal at low bias voltages. This demonstrates that an increase in Schottky barrier resistance decouples the spins in the localized states from the bulk band of silicon, and causes a transition from direct tunneling to a thermionic and localized state assisted tunneling. Our findings provide new insights about the role of Schottky barrier for spin injection, accumulation and detection in silicon.

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8813-42, Session 11

How reliable are Hanle measurements in metals in a three-terminal geometry? *(Invited Paper)*

Oihana Txoperena, Marco Gobbi, Amilcar Bedoya-Pinto, Federico Golmar, Xiangnan Sun, CIC nanoGUNE Consolider (Spain); Luis E. Hueso, CIC nanoGUNE Consolider (Spain) and IKERBASQUE, Basque Foundation for Science (Spain); Felix Casanova, CIC nanoGUNE Consolider (Spain)

Spintronics is a rapidly growing research area that aims to use and manipulate the spin of the electron. There is special interest in purely electrical spin injection and detection in semiconducting devices, to integrate the spin functionality into conventional electronics. A simple device to study spin injection and transport in semiconductors uses a three-terminal (3T) geometry, in which spin accumulation is induced and probed via Hanle effect by a single magnetic tunnel contact. Since the 3T geometry does not require submicron-sized fabrication processes, this type of devices have become very popular. However, many results associated to this method are still controversial, including spin accumulation values well above the theoretical ones, an anomalous bias dependence of the Hanle signal or the unclear origin of the inverted Hanle effect.

We test the validity of Hanle measurements in 3T devices by using aluminum (Al) and gold (Au). The obtained Hanle and inverted Hanle curves show an anomalous behavior. First, we measure signals 8 orders of magnitude larger than those predicted by standard theory. Second, the temperature and voltage dependences of the signal do not match with the tunneling spin polarization of the ferromagnetic contact. Finally, the spin relaxation times obtained with this method are independent of the choice of the metallic channel. These results are not compatible with spin accumulation in the metal. Furthermore, a scaling of the Hanle signal with the interface resistance of the devices suggests that the measured signal is originated in the tunnel junction.

8813-43, Session 11

Spin injection, transport, and relaxation in spin light-emitting diodes: magnetic field effects *(Invited Paper)*

Nils C. Gerhardt, Henning Höpfner, Carola Fritsche, Arne Ludwig, Astrid Ludwig, Ruhr-Univ. Bochum (Germany); Frank Stromberg, Heiko Wende, Werner Keune, Univ. Duisburg-Essen (Germany); Dirk Reuter, Univ. Paderborn (Germany); Andreas D. Wieck, Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

Efficient electrical spin injection into semiconductor based devices at room temperature is one of the most important requirements for the development of applicable spintronic devices in the near future and is thus an important and very active research field. Here we report experimental results for the electrical spin injection in spin light-emitting diodes (spin-LEDs) without external magnetic fields at room temperature. Our devices consist of a Fe/Tb multilayer spin injector with remanent out-of-plane magnetization, an MgO tunnel barrier for efficient spin injection and an InAs quantum dot light-emitting diode. Using a series of samples with different injection path lengths allows us to experimentally determine the spin relaxation during vertical transport from the spin injector to the active region at room temperature. In combination with our concept for remanent spin injection, we are additionally able to investigate the influence of an external magnetic field on the spin relaxation process during transport. While the spin relaxation length at room temperature without external magnetic field is determined to be 27 nm, this value almost doubles if an external magnetic field of 2 Tesla is applied in Faraday geometry. This demonstrates that the results for spin injection and spin relaxation obtained with or without magnetic field can hardly be compared. The efficiency of spin-induced effects is overestimated as long as magnetic fields are involved. Since strong magnetic fields are not acceptable in application settings, this may lead to wrong conclusions and potentially impairs proper device development.

8813-44, Session 12

Electrical spin injection in semiconductors probed by magnetoresistance and spin pumping experiments: the exact role of localized states and related hyperfine interactions *(Invited Paper)*

Henri Jaffrès, Jean-Marie George, Julian Pereiro, Sankara Ruttala, Unité Mixte de Physique CNRS/Thales (France); Matthieu Jamet, Commissariat à l'Énergie Atomique (France)

In this talk review, I will present our latest experiments obtained on electrical spin injection at MgO/Ge interfaces and (Ga,Mn)(As,P)/n+-GaAs Ezaki diodes and probed by magnetoresistance and spin pumping experiments. Our experiments concern the electrical detection of spin accumulation by respective Hanle and Inverted Hanle effects giving specific magnetoresistance associtated to voltage drop or increase and related to the change in the level of spin accumulation. I will discuss the origin of the spin signal enhancement observed at low temperature and related to a preferential spin injection in localized states of semiconductor nearby the ferromagnet/semiconductor interfaces.

In the III-V (Ga,Mn)(As,P)/GaAs Ezaki devices, we interprete the full Hanle curves by the existence of the hyperfine interactions between the spin of carriers injected and the nuclear spins of the Ga and As atomic species within the localized states.

8813-45, Session 12

Non-local versus three-terminal detection of spin accumulation in (Ga,Mn)As/GaAs spin Esaki diode devices *(Invited Paper)*

Mariusz Ciorga, Univ. Regensburg (Germany); Junichi Shiogai, Tohoku Univ. (Japan); Martin Utz, Dieter Schuh, Univ. Regensburg (Germany); Makoto Kohda, Tohoku Univ. (Japan); Dominique Bougeard, Univ. Regensburg (Germany); Tsutomu Nojima, Junsaku Nitta, Tohoku Univ. (Japan); Dieter Weiss, Univ. Regensburg (Germany)

Over the last couple of years there has been a real progress in understanding and realization of electrical spin injection and detection in semiconductors. Detection of spin accumulation is typically realized by means of four-terminal (4T) measurements in non-local (NL) configuration, i.e., with injector and detector circuits separated from each other. The alternative method of spin detection involves three-terminal (3T) measurement where an injector electrode is used also for spin detection. This method has been used especially in cases when non-local signals could not be observed, e.g., in most of the experiments on Si. There have been however many controversies related to the latter method, as measured 3T signals often exceed by orders of magnitude the value expected from a standard model of spin injection.

In the presentation we will discuss the similarities and differences between 3T and 4TNL spin signals observed in spin injection devices based on (Ga,Mn)As/GaAs Esaki diodes. In particular we will discuss in details a dependence of the signal on bias voltage/current applied to the injector. The non-local spin signal decreases with bias as a result of a drop in spin injection efficiency. The 3T signal, on the other hand, shows a very strong enhancement for positive voltages – by two orders of magnitude at the voltage corresponding to the Esaki dip in current-voltage characteristic. We will discuss the observed enhancement in connection to the model involving spin accumulation generated in localized states as well as to the effect of electric field on spin detection sensitivity.

The work was supported by German Science Foundation (DFG) through the project SFB689.

8813-46, Session 12

Dynamical spin injection and spin transport in Si and Ge at room temperature *(Invited Paper)*

Masashi Shiraishi, Osaka Univ. (Japan)

Electrical spin injection methods have been widely used in order to investigate spin transport and relaxation properties in nonmagnetic metals, inorganic semiconductors and organic molecules. Recent establishment of dynamical spin injection, yielding pure spin current in condensed matters, paved a new pass way to spin injection into various materials [1,2], where ferromagnets play a role of “spin battery”. We firstly succeeded in generating pure spin current (not spin-wave spin current) and detecting spin transport in p-Si [3], single layer graphene [4] and Al [5] by using the dynamical method. Furthermore, dynamical spin injection in p-Ge was also succeeded [6]. In this talk, I focus on our recent success on spin pumping in Si and Ge by introducing the detail of spin transport and spin relaxation, especially temperature dependence and doping concentration dependence.

References: [1] S. Mizukami et al., PRB 2002. [2] E. Saitoh et al., APL 2006. [3] E. Shikoh, M. Shiraishi et al., PRL in press. [4] Z. Tang, M. Shiraishi et al., arXiv:1211.0124. [5] Y. Kitamura, M. Shiraishi et al., arXiv:1212.0283. [6] M. Koike, M. Shiraishi et al., APEX in press.

8813-47, Session 12

Spin currents in Ge-based heterostructures *(Invited Paper)*

Federico Bottegoni, Alberto Ferrari, Stefano C. Cecchi, Marco Finazzi, Giovanni Isella, Franco Ciccacci, Politecnico di Milano (Italy)

Germanium has recently become an appealing candidate for spintronics applications, due to the large spin-orbit interaction, long electron spin lifetimes at the L point of the Brillouin zone and the easy integrability with Si-based electronics. In this context, we studied the properties of spin currents optically injected in Ge-based heterostructures and detected using inverse spin Hall effect (ISHE). We characterized the ISHE signal in diffusive regime, as a function of the initial electron spin polarization, generation depth, doping of the structures and externally applied electric fields.

8813-48, Session 13

Fundamental aspects of spin and charge transport in nanoscale systems and ultra-cold atoms *(Keynote Presentation)*

Massimiliano Di Ventra, Univ. of California, San Diego (United States)

I will discuss some of the most basic questions in fermionic and bosonic transport, such as the conditions for the existence of a steady-state current, its uniqueness, the role of interactions and spin statistics, its entanglement entropy, etc. This will lead me to introduce an alternative viewpoint to conduction - the micro-canonical formalism of transport - which is ideal to study the above issues [1]. I will point out the similarities and differences with the widely used Landauer formalism, and advance a series of predictions that can be verified by loading ultra-cold atoms into artificial optical lattices.

[1] M. Di Ventra, Electrical Transport in Nanoscale Systems (Cambridge University Press, 2008).

8813-50, Session 13

Engineering Dirac points with ultracold fermions in optical lattices *(Invited Paper)*

Leticia Tarruell, Institut d'Optique Graduate School (France); Daniel Greif, Thomas Uehlinger, Gregor Jotzu, Tilman Esslinger, ETH Zurich (Switzerland)

Dirac points are central to many phenomena in condensed-matter physics, from massless electrons in graphene to the emergence of conducting edge states in topological insulators. At a Dirac point, two energy bands intersect linearly and the electrons behave as relativistic Dirac fermions. In solids, the rigid structure of the material determines the mass and velocity of the electrons, as well as their interactions. A different, highly flexible means of studying condensed-matter phenomena is to create model systems using ultracold atoms trapped in the periodic potential of interfering laser beams. Here we report the creation of Dirac points with adjustable properties in a tunable honeycomb optical lattice. Using momentum-resolved interband transitions, we observe a minimum bandgap inside the Brillouin zone at the positions of the two Dirac points. We exploit the unique tunability of our lattice potential to adjust the effective mass of the Dirac fermions by breaking inversion symmetry. Moreover, changing the lattice anisotropy allows us to change the positions of the Dirac points inside the Brillouin zone. When the anisotropy exceeds a critical limit, the two Dirac points merge and annihilate each other--a situation that has recently attracted considerable theoretical interest but that is extremely challenging to observe in solids. We map out this topological transition in lattice parameter space and find excellent agreement with ab initio calculations. Our results not only pave the way to model materials in which the topology of the band structure is crucial, but also provide an avenue to exploring many-body phases resulting from the interplay of complex lattice geometries with interactions.

8813-51, Session 14

Chiral spin torque at magnetic domain walls *(Keynote Presentation)*

Stuart S. P. Parkin, IBM Almaden Research Ctr. (United States)

Electronic spin currents provide a powerful means of manipulating magnetization in magnetic memory and logic nano-devices. In particular, the transfer of spin angular momentum derived from currents spin-polarized by volume electron scattering gives rise to a spin transfer torque (STT) that can drive magnetic domain walls (DWs) along nanowires. This bulk-derived STT mechanism, however, weakens as the volume to surface ratio of the nanowire is reduced in ultra-thin magnetic layers: in this case the DWs are found to move in the opposite direction to that expected from bulk STT and, moreover, at much higher speeds. These properties are most pronounced in structures containing interfaces between atomically thin cobalt layers and platinum. Here we show that these properties are due to two intertwined phenomena both derived from spin-orbit interactions at the Co/Pt interfaces. By measuring the influence of magnetic field on current driven DW motion in perpendicularly magnetized Co/Ni/Co trilayers we find that there exists an internal effective magnetic field that operates on each DW. This field, localized at the DWs is oriented along the nanowire but has a direction that alternates between successive DWs, such that, acting in concert with spin Hall currents, the DWs are driven in lock-step along the nanowire. We propose that this chiral effective field arises from a Dzyaloshinskii-Moriya interaction (DMI) at the Co/Pt interfaces. By revealing the origin of this remarkable phenomenon that allows for the highly efficient manipulation of DWs in ultrathin magnetic films, new families of spintronic devices can be anticipated.

8813-52, Session 14

A time-domain method for mapping stochastic dynamics in spin torque oscillators *(Invited Paper)*

Graham E. Rowlands, Cornell Univ. (United States); Jian Zhu, Headway Technologies, Inc. (United States); Jordan A. Katine, HGST (United States); Juergen Langer, SINGULUS TECHNOLOGIES AG (Germany); Ilya N. Krivorotov, Univ. of California, Irvine (United States)

Spin torque from a spin-polarized current can excite magnetization auto-oscillations in the free layers of spin-valves, thereby generating microwave voltages at frequencies tunable by the applied current. These spin-torque oscillators (STOs) may find applications as microwave sources or magnetic field sensors for computer hard drives. Because of the STOs' small sizes, their magnetization dynamics are strongly influenced by ambient thermal fluctuations. For this reason, the microwave signals emitted by STOs typically possess large generation linewidths, a characteristic that is perhaps the primary barrier to industrial applications.

We demonstrate a new method of using time-resolved measurements of STO voltage oscillations to extract new information about these stochastic dynamics. Frequency domain techniques are often used as indirect probes of the coherence properties of the dynamics, while our method allows for direct observation of the time evolution of the magnetization vector. By first performing a careful analysis of the DC electrical properties of a particular STO, we can reconstruct the distributions of angles at which the magnetization trajectories intersect the sample plane. We show that these distributions are accurately

reproduced by the effective energy Fokker-Planck formalism [1,2], and that we may readily extract the bias-dependent strength of the field-like component of spin-torque. Finally we show how the spectra of these devices can be accurately predicted without the need for complicated analytical machinery.

[1] D. Apalkov and P. B. Visscher, J. Magn. Magn. Mater. 286, 370 (2005).

[2] G. Bertotti, I. Mayergoyz, and C. Serpico, Nonlinear magnetization dynamics in nanosystems (Elsevier Science, 2008), ISBN 9780080443164.

8813-53, Session 14

Spin-motive force in solid-state systems *(Invited Paper)*

Stewart E. Barnes, Univ. of Miami (United States)

In MRAM magnetic tunnel junctions (MTJs) spin-motive forces (SMF) [1] are the Newtonian reciprocal of the spin-torque transfer (STT) effect and more generally are associated with ``drag" effects, i.e., the transfer of linear momentum between, e.g., electrons and phonons degrees of freedom. For a MTJ, from the free layer FMR frequency, typically 2-10GHz the basic SMF ~10muV and apparently negligible compared with an applied voltage ~ 1V. However this is multiplied [2] by a large magnification factor M the ratio of R the barrier resistance to r, that of the metallic free layer. As a result the SMF plays a pivotal role in such devices. It explains the observed magneto-resistance and results , e.g., in negative resistances.

[1] Generalization of Faraday's Law to Include Nonconservative Spin Forces, S. E. Barnes and S. Maekawa Phys. Rev. Lett. 98, 246601 (2007)

[2] Theory of spin-motive-forces in ferromagnetic structures. S. E. Barnes in ``Spin Current" eds Sadamichi Maekawa, Sergio O. Valenzuela, Eiji Saitoh and Takashi Kimura (Oxford University Press, 2012)

8813-54, Session 14

Efficient current induced domain wall motion in CoFeB/MgO nanowires with perpendicular magnetic anisotropy *(Invited Paper)*

Su Jung Noh, Tomek Schulz, Tim Zacke, Johannes Gutenberg Univ. Mainz (Germany); Capucine Burrowes, Guillaume Agnus, Dafiné Ravelosona, Univ. Paris-Sud 11 (France); Berthold Ocker, SINGULUS TECHNOLOGIES AG (Germany); Mathias Kläui, Johannes Gutenberg Univ. Mainz (Germany)

A recently investigated material with a perpendicular magnetic anisotropy is CoFeB/MgO [1], which is shown to yield high TMR ratios.[2] High TMR, which requires MgO barriers is suitable for the electrical read-out of a non-volatile shift register device.

In here, we study the domain-wall (DW) writing, shifting and read-out for DW based devices. We fabricate Ta(5nm)/Co20Fe60B20(1nm)/MgO(2nm)/Ta(5nm) nanowire with Hall crosses for DW read-out using the extraordinary Hall effect (EHE). For DW writing, Au bars have been placed across the nanowires for the DW nucleation using local Oersted field generated by a pulse current.

Single DWs can be nucleated at pulse current densities through the Au nanowires of j = 5.64 x 1011 A/ without applying any external fields. We determine the DW nucleation statistics that depends on the pulse length, which can be modelled as a thermally activated process with 100 % nucleation for j = 6.3 x 1011 A/m2.

After the DW preparation at the entrance of the Hall cross, we inject current pulses into the CoFeB/MgO nanowire to shift the DW. The DW can be pushed into the Hall cross at a current density of j = 9.5 x 1010A/m2 with 13 mT of supporting external field. By varying the current and applied fields, we determine the non-adiabaticity from the field-current equivalence [3].

[1] S. Iked et al., Nature Mater. 9, 721 (2010)

[2] S. Fukami et al., Appl. Phys. Lett. 98, 082504 (2011)

[3] J. Heinen et al., Appl. Phys. Lett. 96, 202510 (2010)

8813-55, Session 14

Magnetic resonances driven by an ac current *(Invited Paper)*

Maxim Tsoi, The Univ. of Texas at Austin (United States)

Excitation of ferromagnetic resonance (FMR) by an ac current has been observed in macroscopic ferromagnetic films for decades and typically relies on the ac Oersted field of the current to drive magnetic moments into precession and classical rectification of ac signals to detect the resonance. Recently, current-driven resonances have attracted renewed attention with the discovery of spin-transfer torque (STT) effect [1-3] due to its potential applications in magnetic memory and microwave technologies. Here STT associated with the ac current is used to drive magnetodynamics on the nanoscale that enables FMR studies in sample volumes smaller by a factor of 1000 compared to conventional resonance techniques.

In our experiments we use nanoscale point contacts to produce extremely high-density ac (microwave frequency) currents and study their influence on magnetodynamics in magnetic thin films and multilayers. Here a time-dependent STT associated with the microwave current drives magnetization into resonance and enables STT-FMR [4] studies on the nanoscale. In our experiments we detect both rectified signals and absorption of microwaves that allows for a direct comparison of STT-FMR technique with conventional FMR schemes. At double the FMR frequency we observe the STT-driven parametric resonance [5] which is different from a regular forced resonance (FMR) since the action appears as a time varying modification on the system's parameter – STT produces a time-dependent modulation of the effective damping parameter.
Due to its nonlinear nature, parametric excitation grows significantly faster than the forced excitation and may result in a faster switching of magnetization and, therefore, an increased speed (and reduced power) of logic and memory devices based on STT (e.g. STT-MRAM). This work was supported in part by NSF grant DMR-1207577.

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8813-56, Session 15

Spin-orbit enhanced electric-field control of magnetism in multiferroic BiFeO3 *(Invited Paper)*

Rogerio de Sousa, Univ. of Victoria (Canada)

The ability to control magnetism using electric fields is of great fundamental and practical interest. It may allow the development of ideal magnetic memories with electric write and magnetic read capabilities, as well as logic devices based on spin waves that dissipate much less energy [1]. Multiferroic materials with coexisting magnetic and ferroelectric phases have emerged as the prototypical physical system to search for E-field control of magnetism. Previous demonstrations are based on poling the ferroelectric polarization into another direction in order to force the spins to move into a different easy plane.

Here I will present a microscopic theory [2] that shows that E-field control of magnetism can actually be much more striking, provided the material has strong spin-orbit interaction. I will show that in bismuth ferrite (BiFeO3 or BFO) spin-orbit coupling at the bismuth ion sites results in a special kind of magnetic anisotropy that is linear in the applied E-field, and that this interaction explains the origin of the giant E-field effect on magnons observed in [1]. This interaction can convert the cycloid ground state into a homogeneous antiferromagnet, with a weak ferromagnetic moment whose orientation can be controlled by the external E-field direction. Remarkably, the E-field control of magnetism occurs without changing the ferroelectric state, reducing the energy dissipation in spin-based devices.

[1] P. Rovillain, R. de Sousa, Y. Gallais, A. Sacuto, M.A. Measson, D. Colson , A. Forget, M. Bibes, A. Barthelemy, and M. Cazayous, Nature Mater. 9, 975 (2010).

[2] R. de Sousa, M. Allen, and M. Cazayous, arXiv:1209.6612.

8813-57, Session 15

Large tunnel electroresistance controlled by ferroelectric domain switching in BaTiO3 and BiFeO3- based ferroelectric tunnel junctions *(Invited Paper)*

Vincent Garcia, Unité Mixte de Physique CNRS/Thales (France)

After being conceptualized in the early 1970's, ferroelectric tunnel junctions (FTJs), where an ultrathin ferroelectric film is sandwiched between two electrodes, have remained elusive for more than 30 years. At room temperature, we use piezoresponse force microscopy (PFM) to show robust ferroelectricity in BaTiO3 ultrathin films, and conductive-tip atomic force microscopy to demonstrate the non-destructive resistive readout of the polarization state via its influence on the tunnel current [Nature 460 (2009) 81-84]. Solid-state devices were fabricated out of these ferroelectric tunnel barriers. These FTJs show OFF/ON ratio >100 with fast and low energy resistive switching correlated to ferroelectric switching [Nature Nanotech. (2012) 101-104]. By varying the voltage pulse amplitude, intermediate resistance states are reachable and PFM imaging reveals a direct correlation between resistance and ferroelectric domains configuration. The FTJs behave as memristors where quasi-continuous resistance variations with cumulated voltage pulses in the ns range can be interpreted with standard models of ferroelectric domains dynamics [Nature Mater. 11, 860-864 (2012)]. More recently, we observed giant tunnel electroresistance (OFF/ON ratio >10,000) in solid-state FTJs based on ultrathin films of BiFeO3. Using PFM imaging, we demonstrated that the changes in resistance scale with the nucleation and growth of ferroelectric domains in the ultrathin BiFeO3. These devices emerge as an alternative to other resistive binary or analog memories with the advantage of not being based on voltage-induced migration of matter at the nanoscale, but on a purely electronic mechanism.

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8813-58, Session 15

Exploring symmetry effects in low dimensional transport in SrTiO3-based heterostructures *(Invited Paper)*

Christopher Bell, SLAC National Accelerator Lab. (United States)

At low temperatures bulk SrTiO3 is on the border of ferroelectricity, and can be doped to create a low density superconductor with high electron mobility. These fascinating properties have motivated the recent interest in low dimensional SrTiO3 heterostructures. The conductivity at the asymmetrically confined LaAlO3/SrTiO3 interface [1], and in particular its control with a field effect gate [2, 3], is one example where we can explore novel low dimensional physics. At the same time, studies of symmetrically confined 2D superconductivity and 2D quantum oscillations in Nb:SrTiO3 [4, 5] offer additional control and insights into this fascinating quantum material. This talk will compare and contrast these two different ways of constraining the electrons, noting especially the emergent magnetism in the former system [6], opening the door to intriguing spin transport properties.

[1] A. Ohtomo and H. Y. Hwang, Nature 427, 423 (2004).

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[5] M. Kim et al., Phys. Rev. Lett. 107, 106801 (2011).

[6] J. Bert et al., Nature Phys. 7, 767 (2011).

8813-59, Session 15

Magnetic complex oxide devices: from a diode to a transistor *(Invited Paper)*

Yasuyuki Hikita, SLAC National Accelerator Lab. (United States)

The recent advances in the ability to control interface structures on the atomic scale has allowed new spin devices to be explored using complex oxide materials [1]. One of the major approaches in making devices is the active use of the strong internal electric field at interfaces as in bipolar transistors. Since the operation of such devices is dominated by carrier transport perpendicular to the interface, it is essential to understand and control the interface energy band alignments.

In this talk, I will introduce three studies on heterojunction devices using La0.7Sr0.3MnO3 (LSMO) and Nb-doped SrTiO3 (NSTO). First is the direct observation of Schottky barrier height (SBH) variation with magnetic field using internal photoemission spectroscopy, reflecting strong magneto-orbital coupling in LSMO [2, 3]. Second is the application of interface dipole engineering in controlling the SBH without affecting the properties of the two materials [4]. A change in SBH of 0.5 V was achieved by modifying the interface termination and hence the interface dipole arising from screening of the polarity mismatch at the interface. Finally, I will present successful operation of an "all-oxide" hot-electron transistor which can be a promising platform for future spin-valve transistors given their epitaxial interface structures [5].

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8813-60, Session 16

Optically-induced magnetism in strontium titanate *(Invited Paper)*

Scott A. Crooker, William D. Rice, Los Alamos National Lab. (United States); Chris Leighton, Palak Ambwani, Univ. of Minnesota (United States)

Strontium titanate (SrTiO_3), a nominally diamagnetic semiconducting perovskite, is one of the most extensively investigated complex oxides and is considered a fundamental building block in the emerging field of "oxide electronics". In recent years a variety of fascinating and unexpected phenomena have been discovered in SrTiO_3, both in bulk and at interfaces. Examples include superconductivity at the lowest known electron densities, coexisting quantum oscillations and superconductivity, two-dimensional electron gas formation at interfaces, and even suggestion of local moment formation and magnetic order [1]. These discoveries have motivated a renewed interest in the electronic, magnetic, and optical properties of such complex oxide materials.

Here we demonstrate that a long-lived and persistent magnetization can be optically induced (and optically detected) in bulk doped single crystals of strontium titanate [2]. In analogy with the phenomenon of optical spin orientation that is widely exploited in III-V semiconductors, we find that magnetic circular dichroism studies reveal clear evidence of induced magnetization in SrTiO_3 at zero applied field. These signals are confirmed with SQUID magnetometry. Interestingly, and in contrast to III-V semiconductors, the optically-induced magnetism in SrTiO_3 is extremely long-lived. We discuss relevant mechanisms that lead to the observed phenomena.

[1] e.g., A. J. Millis, Nature Physics 7, 749 (2011) and references therein

[2] W.D. Rice, M. Bombeck, J. D. Thompson, S. A. Crooker, P. Ambwani & C. Leighton, submitted

8813-61, Session 16

Tailoring 'materials on the verge' in magnetic oxide heterostructures *(Invited Paper)*

Anand Bhattacharya, Argonne National Lab. (United States)

The complex oxides have many electronic and structural phases, which arise as a result of electron-electron and electron-lattice interactions. These phases often compete, and we can usually tune between them by doping charge carriers. An alternative to this approach is to carry this out in a reversible manner by applying an external field. The key to achieving this tunability is to tailor materials that are on the verge of a phase transition where they have a strong susceptibility to external fields. In our work with manganite superlattices, we have shown that it is possible to create quasi two-dimensional regions of a ferromagnetic (FM) metal within an antiferromagnetic (AF) host by exploiting the competition between double-exchange ferromagnetism and AF superexchange. We created this delta-doped material by adding a single atomic layer of dopant cations to the host AF material. The doped electrons cause the AF spins in the vicinity of the dopant cations to cant in a manner that was first predicted by de Gennes but has remained elusive experimentally. This material could be a candidate for electric field-effect and ferroelastic strain tuning between FM and AF phases. We demonstrate our approach with a study of another double-exchange ferromagnet, Fe3O4, where we use ferroelastic strain to carry out non-volatile resistive switching over a broad range of temperatures, including in the vicinity of the Verwey metal-insulator transition where we observe the largest susceptibility of resistance to ferroelastic strain.

8813-62, Session 16

Fast strain driven dynamics: magnetization rotation of Co/Pt and antiferromagnetic ordering in Cr2O3 *(Invited Paper)*

Shireen Adenwalla, Univ. of Nebraska-Lincoln (United States) and Nebraska Ctr. for Materials and Nanoscience (United States); Uday Singh, William Echtenkamp, Christian Binek, Univ. of Nebraska-Lincoln (United States)

We are able to generate large (1%), fast (GHz) dynamics strains by patterning piezoelectric substrates with appropriately curved electrodes. The electrode curvature focuses the strain energy into a focal spot. We use this large strain to drive two technologically important materials, perpendicular magnetic anisotropy Co/Pt and the antiferromagnet Cr2)3, which has been shown to allow for electrical control of exchange bias. In the first set of experiments, thin films of Co/Pt are patterned at the focal spot and by using the large strain and the magnetoelastic coupling, we attempt to overcome the strong perpendicular anisotropy of these thin films, rotating the magnetization into and out of the plane at GHz frequencies. The 2nd set of experiments involves thin films of the antiferromagnetic magento-electric Cr2O3. Strain coupling alters the ordering temperature and we drive the material back and forth across the transition temperature using fast dynamic strain. In both cases, we use the magneto-optical Kerr effect (MOKE) to monitor the transitions. We present both dc time averaged data and preliminary data at the high driving frequencies of the curved transducers.

8813-63, Session 16

Engineering magnetism and transport at perovskite cobaltite interfaces via oxygen vacancy ordering *(Invited Paper)*

Shameek Bose, Manish Sharma, Maria Torija, Univ. of Minnesota, Twin Cities (United States); Jaume Gazquez, Oak Ridge National Lab. (United States) and Univ. Complutense de Madrid (Spain); Maria Varela, Oak Ridge National Lab. (United States); Josh Schmitt, Chunyong He, Univ. of Minnesota, Twin Cities (United States); Julie Borchers, Mark Laver, National Institute of Standards and Technology (United States); Sami El-Khatib, Univ. of Minnesota, Twin Cities (United States) and American Univ. of Sharjah (United Arab Emirates); Valeria Lauter, Haile Ambaye, Rick Goyette, Oak Ridge National Lab. (United States); Chris Leighton, Univ. of Minnesota, Twin Cities (United States)

Thin films and heterostructures of perovskite cobaltites are of significant interest both for fundamental issues in magnetism (e.g. spin-state crossovers, magnetic phase separation), and for applications in oxide devices (e.g. solid oxide fuel cells, oxide spintronics). In our recent work on the prototypical SrTiO3(001)/La1-xSrxCoO3 system we demonstrated that interface-induced magneto-electronic phase separation dominates the properties of such systems, driven by accumulation of oxygen vacancies at the interface [1]. This results from a novel mechanism for accommodation of lattice mismatch with the substrate based on formation and long-range ordering of oxygen vacancies [2], thus providing a fundamental link between strain state and oxygen vacancy density. With this link understood, in this work we demonstrate how interfacial magnetic and electronic properties can be fine-tuned by controlling oxygen vacancy ordering via heteroepitaxial strain and crystallographic orientation [3]. In particular, we show that manipulation of the ordering vector of the oxygen defect superstructure can induce dramatic improvements in strain relaxation and thus magnetic and transport properties.

Work at UMN supported by DoE (neutron scattering) and NSF. Work at ORNL supported by DMS&E, DoE. Work at UCM supported by the European Research Council.

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8813-64, Session 17

Giant spin Hall effect induced by skew scattering from large SO impurities in copper *(Invited Paper)*

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The spin Hall effect (SHE) is a key ingredient for future spintronic devices since it enables to convert charge currents into spin currents or vice-versa without ferromagnets and magnetic fields. Platinum is generally accepted to be the best SHE material exhibiting a spin Hall (SH) angle of a few percent. However it is a costly metal, unsuitable for the practical application. In this work, we have studied extrinsic SHEs in Cu-based

alloys such as CuIr and CuBi alloys, as alternative SHE materials.

To estimate the SH angle we have used two models; a purely 1D model and 3D spin transport model based on the Valet-Fert formalism. We found that for Pt and CuIr alloys whose spin diffusion lengths are smaller than the thickness, the SH angles obtained from the 1D and 3D models do not differ significantly (about 0.02). For CuBi alloys, on the other hand, the SH angle we obtain is much larger than that of Pt and CuIr, which is consistent with a recent ab-initio calculation. However the analysis in the 3D model gives a larger SH angle (-0.24 for 3D compared to -0.12 for 1D). The difference between the 1D and 3D models comes from the correction by the 3D model of the spreading of the spin accumulation over the sides of the contact when the spin diffusion length is relatively long. CuBi appears to be a very promising SHE material for spintronics.

8813-66, Session 17

Magnetic damping in nanometer-thick yttrium iron garnet films *(Invited Paper)*

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Spin waves have garnered increased attention lately due to their potential use for low-power information processing. Towards this end, ferromagnetic insulators, such as yttrium iron garnet (YIG), are of high interest, since they offer very low damping for magnetization dynamics, and hence, long spin-wave life times and propagation distances. For practical applications, as well as for fundamental science studies there is high demand of very thin YIG films, which still preserve the advantageous properties of the bulk materials. Here we present the growth and characterization of nanometer-thick YIG films prepared by pulsed laser deposition (PLD), which were optimized to have magnetic damping that is only a factor of ten above intrinsic bulk values [1]. Combining these films with thin layers of Pt allows modulation of the damping via electric charge currents [2]. In this case the spin Hall effects in Pt [3] give rise to a net spin accumulation at the Pt/YIG interface, which then through interfacial spin scattering can exert a torque on the magnetization in the YIG layer, so that the damping is decreased or increased, depending on the charge current direction. Furthermore, the presence of Pt gives rise to an unexpected additional magnetic damping, which may be correlated with induced magnetic moments in the Pt layer.

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8813-67, Session 17

Dynamic measurement of spin Hall effects in nonmagnetic/ferromagnetic bilayer films *(Invited Paper)*

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Spin Hall effect (SHE) is well known as an effective method for generating pure spin currents without using ferromagnetic materials. The ratio between input charge current density Jc and output spin current density Js is defined as spin Hall angle Js/Jc. Until now, several groups have reported different spin Hall angles for Pt using different measurement techniques. For example, L. Q. Liu et. al. have recently demonstrated the spin Hall angle determined by dynamic measurements based on spin torque ferromagnetic resonance (ST-FMR) in nonmagnetic/ferromagnetic bilayer films. However systematic experiments for quantitative evaluation of spin Hall angle is lacking. Therefore, we have systematically studied the film thickness dependence of Js/Jc in ST-FMR spectrum to estimate the exact value of spin Hall angles for Pt, Pd, Ta, Mo and Ru.

8813-109, Session 17

Controlling domain wall motion by an electric field in Ta-CoFeB-MgO ultra-thin films with perpendicular anisotropy *(Invited Paper)*

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No Abstract Available

8813-68, Session 18

A theory of quantum dynamics of a nanomagnet under excitation *(Keynote Presentation)*

Lu Jeu Sham, Univ. of California, San Diego (United States)

A quantum treatment of magnetization dynamics of a nanomagnet between a thousand and a million spins may be needed as the magnet interacts with quantum control. The advantage of the all-quantum approach over the classical treatment of magnetization is the accounting for the correlation between the magnet and the control agent and the first-principles source of noise. This talk will concentrate on an overview of the theory with a presentation of the basic ideas which could have wide applications and illustrations with some results. Details of applications to specific models are or will be published elsewhere. A clear concept of the structure of the ground and excited macrospin states as magnetization rotation states and magnons in the Bloch/Dyson sense gives rise to a consistent theory of the magnetization dynamics of a ferromagnet modeled by the Heisenberg Hamiltonian. An example of quantum control is the spin torque transfer, treated here as a sequence of scatterings of each current electron with the localized electrons of the ferromagnet, yields in each encounter a probability distribution of the magnetization recoil state correlated with each outgoing state of the electron. This picture provides a natural Monte Carlo process for simulation of the dynamics in which the probability is determined by quantum mechanics. The computed results of mean motion, noise and damping of the magnetization will be shown.

*Work done with Yong Wang, Shengnan Ji, and Tiamhock Tay, supported by US Army Research Office MURI award W911NF0910406, NSF/NEB DMR-1124601, and NSF ECCS-1202583.

8813-69, Session 18

Pulsed optical excitation of ordered spin systems in the weak excitation regime *(Invited Paper)*

Hiro Munekata, Kosuke Yamamoto, Takashi Mastuda, Kazuhiro Nishibayashi, Yoshitaka Kitamoto, Nozomi Nishizawa, Tokyo Institute of Technology (Japan)

Investigation of optical excitation of ordered-spin systems has given us the opportunity of pursuing fundamental limit for manipulation of magnetization as well as developing novel devices in optoelectronics and photonics, such as optical buffer memory and latchets. Photo-induced precession of magnetization is an interesting phenomenon in the sense that the energy of ultra-short laser pulses is stored in part for relatively long duration in a spin system in the form of precession. This phenomenon has been studied in various magnetic materials, including metals, semiconductors, and insulators. In this presentation, we are concerned with photo-induced precession of magnetization in ferromagnetic, ultra-thin Co/Pd multi-layer films at excitation fluence as low as 0.25 microJ/cm^2 per a laser pulse of 150 fs, the regime of low energy excitation. This has been achieved with the sample whose Co and Pd layer thicknesses are, respectively, 0.78 nm and 0.81 nm, in which magnetic property of meta-stable fcc Co layers is affected through the magnetic proximity effect in Pd layers. A model which connects precession amplitude and parameters associated with spin dynamics has been developed, through which efficiency of energy transfer between electron and spin sub-systems has been examined quantitatively. Thermal and non-thermal contributions in the weak excitation regime have also been examined in the time domain shorter than 10ps for both Co/Pd multi-layers and (Ga,Mn)As epitaxial layers, from which we point out that the thermal influence appears in the form of a tiny ultrafast demagnetization in the former whereas it is often absent in the later.

8813-70, Session 18

Reversal of magnetization of small magnetic particles by the ac field *(Invited Paper)*

Dmitry A. Garanin, Liufei Cai, Eugene M. Chudnovsky, Lehman College (United States)

Numerical and analytical studies of the magnetization reversal of a single-domain magnetic particle by a circularly polarized ac field of time-dependent frequency are performed. An advantage of the circular polarization is that magnetic field is precessing in sync with the magnetization thus providing a sustained reversal torque. For the time-linear frequency sweep, the phase diagrams are computed that illustrate the dependence of the reversal on the frequency sweep rate v, the amplitude of the ac field h, the magnetic anisotropy field d, and the damping parameter α. The necessary condition of the reversal is $h > \alpha d$. The maximal energy efficience is reached in the middle of this interval. Further, if the frequency sweep is too fast, the magnetization cannot follow and does not reverse. If the frequency sweep is too slow, an instability develops in the middle of reversal and reversal becomes uncontrolled. In the optimal case the spin is adiabatically following the frequency sweep so that it remains on resonance during the whole reversal. The most efficient magnetization reversal requires a nonlinear time dependence of the frequency, $\omega(t)$, for which an exact analytical formula is derived with account of damping. Implementation of a small-scale magnetization reversal is proposed in which a nanomagnet is electromagnetically coupled to two weak superconducting links controlled by the voltage. The dynamics of such a system is analyzed with account of the back effect of the magnet on the superconducting links that is shown to be detrimental for the reversal.

8813-110, Session 18

Current-induced spin polarization and the spin Hall effect in a clean bilayer system

Felix G. G. Hernandez, Leonardo M. Nunes, Gennady M. Gusev, Univ. de São Paulo (Brazil); Askhat K. Bakarov, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation)

The experimental demonstration of the spin Hall effect in a two-subband system is reported. The sample consist of a high mobility two-dimensional electron gas in a symmetric wide quantum well. The spatial dependence is studied by Kerr rotation as function of the external magnetic field using the applied electric field amplitude and direction as control parameters. We observe that the effect is robust in the bilayer structure leading to opposite spin accumulation near the edges of a Hall bar. We found an electrically controllable internal magnetic field (nonzero Rashba coefficient), a large spin Hall conductivity, and a mobility-enhanced spin diffusion constant in the Fermi liquid regime. The data was analyzed following both phenomenological and microscopic theoretical approaches and compared with experimental references of bulk samples in the single layer configuration.

8813-106, Session PWed

Multiferroic nanomagnetic logic: ultra low-power hybrid spintronics-straintronics

Mohammad Salehi Fashami, Noel D'Souza, Virginia Commonwealth Univ. (United States); Kamaram Munira, The Univ. of Alabama (United States); Avik Ghosh, Univ. of Virginia (United States); Supriyo Bandyopadhyay, Jayasimha Atulasimha, Virginia Commonwealth Univ. (United States)

It has been recently shown by the authors that multiferroic nanomagnets (consisting of a piezoelectric and a magnetostrictive layer) can serve as excellent bistable switches for digital information processing since they dissipate a mere ~100 KT per switching event at clock rates of ~1 GHz at room temperature. This is 3-4 orders of magnitude more energy efficient than CMOS. Such multiferroic nanomagnets can function as memory elements in isolation or be laid out in specific geometric shapes and patterns to implement logic gates through dipole coupling. Furthermore, they can implement associative memory elements and multi-state logic . This talk will focus on(i) the magnetization dynamics of such dipole-coupled multiferroic nanomagnets clocked by mechanical stress, modeled by solving the Landau-Lifshitz (LL) equations,(ii) We will theoretically demonstrate operation of a universal logic gate with fan-out and unidirectional logic flow in the gate,(iii) A preliminary study of the reliability of such gates, determined by solving the stochastic LL equations will also be presented , and (iiii) Finally, experimental progress on logic propagation in chains of stress clocked nanomagnets will be discussed.

8813-107, Session PWed

Optical generation of spin imbalance in Si nanowires

Paulo E. Faria Jr., Univ. de São Paulo (Brazil); Guilherme M. Sipahi, Igor Zutic, Univ. de São Paulo (Brazil) and Univ. at Buffalo (United States)

In addition to its central role in conventional electronics, silicon has spin-dependent properties (such as long spin relaxation and decoherence times) that could be particularly useful in spin-based quantum-information processing and spintronics [1]. Unfortunately, its indirect band gap precludes using the standard optical methods of spin injection and detection in semiconductors. However, this obstacle can be removed in Si nanowires which display direct band gap and could also serve as

spin interconnects by modulating spin polarization [2]. Using the k.p method we study the feasibility of optical spin injection in Si nanowires and quantify the degree of spin polarization, given in terms of carriers and spin injection rates [3]. Supported by FAPESP and CNPq, US ONR, NSF-ECCS, DOE-BES, and NSF-NRI.

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8813-72, Session 19

Crossed persistent spin helices *(Invited Paper)*

Carlos Egues, Univ. de São Paulo (Brazil)

In Rashba-Dresselhaus quantum wells with tuned couplings spin-density-wave patterns that are not susceptible to any type of spin-independent and/or electron-electron scatterings are possible. These long-lived persistent spin helices arise from the partial cancellation of the equal-strength Rashba and Dresselhaus spin-orbit terms which gives rise to a fixed spin quantization axis [1]. These robust excitations have been recently realized [2]. Two-subband quantum wells offer the possibility to obtain two distinctively gate-tunable Rashba couplings – including their signs – within a single system [3]. We have investigated the possibility for crossed persistent spin helices in realistic two-subband wells with orthogonal spin quantization axes for the first and second subband [4]. We find unique two-dimensional spin textures resulting from the coherent interference between the two crossed spin helices. We have performed a detailed self-consistent calculation of all relevant spin-orbit coupling parameters of our wells: i. e., the Rashba and Dresselhaus couplings within each subband and the corresponding intersubband couplings. We have also investigated the spin lifetime of the crossed spin helices. Interestingly, we find that for some parameter range the intersubband spin-orbit contributions can enhance the spin lifetimes. Transient spin grating spectroscopy [5] can, in principle, be used to probe these novel spin-density excitations. My collaborators in this work are J. Fu, P. H. Penteado, M. O. Hachiya, and D. Loss. This work has been supported by: CNPq, FAPESP and PRP/USP (Q-NANO).

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8813-73, Session 19

Nonlocal formulation and dimensionality-crossover effects for spin Coulomb drag in low dimensional structures *(Invited Paper)*

Irene D'Amico, The Univ. of York (United Kingdom); Carsten A. Ullrich, Univ. of Missouri (United States)

In spintronic devices some sources of dissipation can be controlled, for example by reducing disorder, whereas others are intrinsic and hence unavoidable. This is the case for the spin Coulomb drag (SCD) effect [PRB-62-4853-2000], which occurs when different spin populations move with different velocities while exchanging momentum via Coulomb scattering: even without spin-flip mechanisms, a spin current will decay due to Coulomb interactions between different spin populations. As a consequence the SCD may significantly reduce spin diffusion [EPL-55-566-2001, Nature-437-1330-2005, Nature-Phys-8-153-2012], and cause intrinsic damping of collective spin-excitations [PRB-74-121303(R)-2006, PRL-109-166401-2012].

Here we focus on SCD as intrinsic damping of intersubband spin plasmons in semiconductor quantum wells. In earlier work [PRB-74-121303(R)-2006], the spin plasmon linewidth was calculated within a linear response formalism where the SCD was treated using a local density approximation (LDA). However recent experiments [PRL-109-166401-2012] show that this formalism, although giving the right order of magnitude, significantly overestimates the actual spin plasmon linewidth. Situations in which LDA breaks down may reveal new insights into the behavior of interacting quantum systems. The description of SCD line broadening of spin plasmons is such a case: as we show, the failure of LDA is related to the crossover between two-dimensional and three-dimensional behaviour of the intersubband dynamics in quantum wells. We derive a new formalism for the spin Coulomb drag which accurately includes both spatial inhomogeneity and quantizations in the growth direction. This new formulation is crucial to accurately and correctly model dissipation in low dimensional structures, where inhomogeneity and dimensionality-crossover effects are important.

8813-74, Session 19

Spin-photonic devices based on (110) quantum wells *(Invited Paper)*

Hitoshi Kawaguchi, Nara Institute of Science and Technology (Japan)

We fabricated a (110) VCSEL with GaAs/AlGaAs MQWs, and demonstrated circularly polarized lasing with a high degree of circular polarization at RT that originated from a long electron spin relaxation time (τs) [1]. Lasing was observed in the one circularly polarized mode over a wide wavelength range from 838 to 857nm, in which a degree of circular polarization higher than 0.8 was maintained [2].

We also investigated carrier lifetime (τc) and τs in (110) GaAs/AlGaAs MQW micro-posts and found that the long τs is preserved even when the sidewall boundaries with fast surface recombination are introduced and the τc is drastically shortened [3]. We precisely measured the τs in the microposts using a pump-probe technique. A long τs of 0.74ns was obtained even for 0.5τm posts in which the τc was drastically shortened to 27ps. Such long τs and short τc are suitable for fast switching of lasing circular polarizations in VCSELs [4].

Moreover, we fabricated a (110) p-i-n structure with a GaAs/AlGaAs MQW and demonstrated a tenfold modulation of the τs by an external electric field at RT [5].

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8813-75, Session 19

Spin-orbit induced magnetoanisotropies in ferromagnet/semiconductor junctions *(Invited Paper)*

Jaroslav Fabian, Martin Gmitra, Alex Matos-Abiague, Univ. Regensburg (Germany); Claudia Draxl, Humboldt-Univ. zu Berlin (Germany)

Spin-orbit fields are phenomenological manifestations of spin-orbit coupling in materials and materials structures lacking space inversion symmetry, which is the majority of technologically important systems: metal surfaces, semiconductor interfaces, ferromagnetic tunnel junctions, graphene on a substrate, surfaces of topological insulators. They all have unique spin-orbit fields that determine spin relaxation, persistence spin helix, spin Hall conductivity, quantum spin Hall protection of the edge states, anisotropic magneto-transport, or magneto-optical phenomena, to name the most important. Each structure has its own spin-orbit field---a sort of spin-orbit DNA. The question is how to determine it for a general electron state and how to control it effectively. In this talk I present a solution for a Fe/GaAs interface which is important for electrical spin injection and magnetotransport tunneling and lateral transport experiments. The spin-orbit fields are extracted from first principles. I will demonstrate how the spin-orbit fields depend on the Fe magnetization orientation, which proves the concept of the magnetic control of spin-orbit coupling in general. I will also discuss related anisotropic magnetotransport experiments. I acknowledge funding from DFG SFB 689.

8813-76, Session 20

Spin transport in single and bilayer graphene *(Invited Paper)*

Gernot Guntherodt, Frank Volmer, Eva Maynicke, Mark Droegeler, Tsung-Yeh Yang, Julia Samm, Syed Rizwan Ali, Mihaita Popinciuc, Bernd Beschoten, RWTH Aachen (Germany); Jayakumar Balakrishnan, Ahmet Avsar, M. Zeng, J. Setiawan, Barbaros Özyilmaz, National Univ. of Singapore (Singapore)

Carrier mobilities over 100.000 cm2/Vs have excited strong interest in graphene for future electronics devices. Moreover, graphene is considered as a promising candidate for spintronics applications. The reason is the weak spin-orbit coupling, the absent hyperfine interaction and the observation of micrometer long spin relaxation lengths [1]. So far most spin transport studies have focused on single layer graphene (SLG). However, bilayer graphene (BLG) has unique electronic properties, which differ greatly from those of SLG by its effective mass of charge carriers, interlayer hopping and electric-field induced band gap. Our studies of spin transport in BLG as a function of mobility, minimum conductivity, charge carrier density and temperature reveal the importance of the D'yakonov - Perel' (DP)-type spin dephasing mechanism [2]. In BLG samples, the spin dephasing time scales inversely with the charge carrier mobility both at room temperature and at low temperatures. Spin dephasing times of up to 2 ns are observed in samples with the lowest mobility. Most remarkably, we observe also a similar inverse scaling of the spin dephasing times and the charge carrier mobility in SLG samples [3]. We demonstrate the role of adatoms and of tunneling vs. transparent Co/MgO/graphene contacts for the manipulation of the spin dephasing times.

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8813-77, Session 20

A graphene solution to conductivity mismatch: spin injection from ferromagnetic metal/graphene tunnel contacts into silicon *(Invited Paper)*

Olaf M. van 't Erve, Connie H. Li, Adam Friedman, Enrique Cobas, Jeremy T. Robinson, Berend T. Jonker, U.S. Naval Research Lab. (United States)

We will show that a FM metal / monolayer graphene contact serves as a spin-polarized tunnel barrier contact which successfully circumvents the classic metal / semiconductor conductivity mismatch issue for electrical spin injection. We demonstrate electrical injection and detection of spin accumulation in Si above room temperature, and show that the corresponding spin lifetimes correlate with the Si carrier concentration, confirming that the spin accumulation measured occurs in the Si and not in interface trap states.

An ideal tunnel barrier should exhibit several key material characteristics: a uniform and planar habit with well-controlled thickness, minimal defect / trapped charge density, a low resistance-area product for minimal power consumption, and compatibility with both the FM metal and semiconductor, insuring minimal diffusion to/from the surrounding materials at temperatures required for device processing.

Graphene, offers all of the above, while preserving spin injection properties, making it a compelling solution to the conductivity mismatch for spin injection into Si. Although Graphene is very conductive in plane, it exhibits poor conductivity perpendicular to the plane. Its sp2 bonding results in a highly uniform, defect free layer, which is chemically inert, thermally robust, and essentially impervious to diffusion. The use of a single monolayer of graphene at the Si interface provides a much lower RA product than any film of an oxide thick enough to prevent pinholes (~ 1 nm).

Our results identify a new route to low resistance-area product spin-polarized contacts, a crucial requirement enabling future semiconductor spintronic devices which rely upon two-terminal magnetoresistance, including spin-based transistors, logic and memory.

8813-78, Session 20

Probing magnetic moment formation in graphene through the scattering of pure spin currents *(Invited Paper)*

Adrian Swartz, Kathleen McCreary, Wei Han, Jen-Ru Chen, Univ. of California, Riverside (United States); Jaroslav Fabian, Univ. Regensburg (Germany); Roland K. Kawakami, Univ. of California, Riverside (United States)

Graphene's two dimensional nature and high surface sensitivity have led to fascinating predictions regarding induced spin-based phenomena through careful control of adsorbates on the graphene surface, including the extrinsic spin Hall effect, band gap opening, and induced magnetism. By taking advantage of atomic scale control provided by MBE, we have investigated submonolayer deposition of adsorbates and their interactions with graphene. Spin transport measurements performed in-situ during systematic introduction of atomic hydrogen demonstrated that hydrogen adsorbed on graphene forms magnetic moments that couple via exchange to the injected spin current. The effects of induced magnetic moments are evident in the non-local magnetoresistance and Hanle spin precession. The observed behavior is quantitatively explained utilizing a phenomenological theory for scattering of pure spin currents by localized magnetic moments. Ar sputtering introduces lattice vacancies and demonstrated similar behavior, indicating that the origin of the induced moments are due to so called pz-orbital defects. On the other hand, experiments with charge impurity scatterers such as Mg, are noticeably absent of features related to magnetic moment formation. Furthermore, we observe effective exchange fields due to the spin-spin coupling between conduction electrons and magnetic moments, which are of interest for novel phenomena and spintronic functionality but have not been seen previously in graphene. The exchange fields cause increased spin precession leading to enhanced effective g-factors, which demonstrate a dependence on the electrostatic back gate voltage, and also leading to new interpretations of Hanle spin precession data and analysis.

8813-79, Session 20

Graphene magnetic tunnel junctions *(Invited Paper)*

Enrique Cobas, Adam L. Friedman, Olaf M. van 't Erve, Jeremy T. Robinson, Berend T. Jonker, U.S. Naval Research Lab. (United States)

Graphene has been shown to be an extraordinary material with record-setting room temperature conductivity and carrier mobility and spin diffusion lengths approaching 100um. However, most research has focused on its excellent in-plane transport properties, neglecting its very different out-of-plane properties. Graphene's 2D nature leads to poor inter-layer coupling and transport, highlighted by graphite's conductance anisotropy of 10,000:1. Graphene's discrete monolayer habit, thermal stability and lack of dangling bonds lend themselves to application as an ultra-thin tunnel barrier. It's lack of spin-orbit coupling promises applications in magnetic tunnel junctions. Moreover, recent band structure arguments predict excellent spin filtering across ferromagnet-graphene interfaces.

We will discuss our fabrication and measurements of ferromagnet-graphene-ferromagnet junctions utilizing NiFe, CVD-grown graphene and Co in a fully scalable photolithographic process. The junctions exhibit non-linear I-V transport properties with weak temperature dependence consistent with tunneling-transport devices. Moreover, we observe spin-polarized tunneling with the characteristic parallel-antiparallel switching of magnetic tunnel junctions. The tunneling magnetoresistance reaches two percent at low temperature and low bias but remains observable even at room temperature. The effect exhibits the expected asymmetric bias dependence due to the different materials on either side of the graphene and its temperature dependence is examined and fitted well using a temperature-dependent modification of the Julliere model previously published by Shang et al.

This work demonstrates the application of graphene as a tunnel barrier in the out-of-plane direction both for charge and spin-polarized charge and has implications for electronics and spintronic devices, including tunnel transistors, magnetic tunnel junctions and spin-transfer torque devices.

8813-80, Session 21

Ultrafast spin-polarized vertical-cavity surface-emitting lasers *(Invited Paper)*

Nils C. Gerhardt, Henning Höpfner, Mingyuan Li, Hendrik Jähme, Ruhr-Univ. Bochum (Germany); Thorsten Ackemann, Univ. of Strathclyde (United Kingdom); Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

Spin-polarized lasers are highly attractive spintronic devices providing characteristics superior to their conventional purely charge-based counterparts. Spin-polarized vertical-cavity surface emitting lasers (spin-VCSELs) promise to offer lower thresholds, enhanced emission intensity, spin amplification, full polarization control, chirp control and ultrafast dynamics. In particular, the ability to control and modulate the polarization state of the laser emission with extraordinarily high frequencies is very attractive for many applications like broadband optical communication and ultrafast optical switches.

After briefly reviewing the state of research in this emerging field of spintronics, we present a novel concept for ultrafast spin-VCSELs which has the potential to overcome the conventional speed limitation for directly modulated lasers and to reach modulation frequencies significantly above 100 GHz. The concept is based on the coupled spin-photon dynamics in birefringent micro-cavity lasers. By injecting spin-polarized carriers in the VCSEL, oscillations of the coupled spin-photon system can by induced which lead to oscillations of the polarization state of the laser emission. These oscillations are decoupled from conventional relaxation oscillations of the carrier-photon system and can be much faster than these. Utilizing these polarization oscillations is thus a very promising approach to develop ultrafast spin-VCSELs for high speed optical data communication in the near future.

Different aspects of the spin and polarization dynamics, its connection to birefringence and bistability in the cavity, and the limitations of this novel approach will be analysed theoretically and experimentally for spin-polarized VCSELs at room temperature.

8813-81, Session 21

Electrical helicity switching with dual-electrode Fe/AlOx/GaAs-based spin-LED *(Invited Paper)*

Nozomi Nishizawa, Hiro Munekata, Tokyo Institute of Technology (Japan)

Spin light emitting diode (spin-LED) would be a device with great possibility in view of a new circular polarized light (CPL) source aiming at future applications such as all-optical magnetic writing, 3-D display, and chiral resolution. For practical application, realization of electrical helicity switching without using an external magnetic field is one of key issues. Reported here is the demonstration of electrical helicity switching using one spin-LED chip having two ferromagnetic Fe electrodes with different coercive force prepared on a GaAs-based double heterostructure (DH) incorporating a 500-nm thick $In_{0.03}Ga_{0.97}As$ active layer. The DH has an AlOx tunneling barrier layer on top of it. Electrical helicity switching has been realized by electrically selecting one of the two Fe electrodes with antiparallel magnetization configuration, as has manifested itself in electroluminescence (EL) extracted from cleaved side-wall of spin-LED. In fact, EL spectra at 5 K have exhibited opposite sign of circular polarization (CP), reflecting antiparallel configuration; the magnitude of circular polarization from one particular device has been P_{circ} = +14 % and -7 %. CP was observed up to around 70 K. When we switched between the two electrodes, a clear helicity switching between right and left polarization was observed, whereas, when passing current simultaneously through two electrodes, P_{circ} ~ 0. This fact can be understood in terms of mixing two opposite circular polarization, yielding linearly polarized light. Tuning the current ratio between two electrodes has yielded smooth conversion between circular and linear polarization.

8813-82, Session 21

Semiconductor optical isolators for integrated optics *(Invited Paper)*

Hiromasa Shimizu, Tokyo Univ. of Agriculture and Technology (Japan)

Optical isolators are one of the indispensable devices to protect semiconductor laser diodes (LDs) from backward reflected light in integrated optics. In order to realize optical isolators, nonreciprocal propagation of light (breaking of time inversion symmetry) is necessary, which can be realized by magnetic materials. Conventional optical isolators are composed of Faraday rotators and two polarizers. Ferrimagnetic garnets are widely used as magneto-optic materials exhibiting Faraday rotation. However, these optical components are not compatible with integrated optics. Therefore, semiconductor optical isolators for integrated optics have been strongly desired. Recently, these integrated optics have been expected on Si as well as III/V waveguides in order to integrate them with electronic driving circuits in optical transmitters and receivers. Semiconductor optical isolators, where semiconductor and ferromagnetic materials are integrated, are one of the most important applications in spin-optics.

We have developed semiconductor optical isolators based on nonreciprocal loss, where the ferromagnetic metals are deposited on semiconductor optical amplifier (SOA) waveguides. Ferromagnetic metals provide the optical isolation owing to the transverse magneto-optic Kerr effect, and the SOA gain compensates the propagation loss by the ferromagnetic metals. We have demonstrated optical isolation of 14.7 dB/mm 1), monolithic integration with LDs 2), and optical isolation with amplifying characteristics 3). These advantages of semiconductor optical isolators are promising for integrated optics.

1) H. Shimizu et al., J. Lightwave Technol. 24 (2006) 38. 2) H. Shimizu et al., IEEE Photonics Technol. Lett. 19 (2007) 1973. 3) H. Shimizu et al., Appl. Phys. Express 4 (2011) 022201.

8813-83, Session 21

Experiment and simulation of spin resolved photoconductivity in mesoscopic devices *(Invited Paper)*

Steven K. Clowes, Juerong Li, Univ. of Surrey (United Kingdom); Adam M. Gilbertson, Imperial College London (United Kingdom); Konstantin L. Litvinenko, Univ. of Surrey (United Kingdom); Lesley F. Cohen, Imperial College London (United Kingdom)

Optical orientation of spins using modulated circularly polarised light provides a highly sensitive technique to study spin dependent transport in mesoscopic semiconductor devices. Recently, we have reported on two studies where this technique was successful in electrically detecting the spin orientation of photo-excited electrons. The mechanics behind these measurements is that in weak magnetic fields the charge carrying electrons exhibit spin sensitive cyclotron motion in the highly spin-orbit coupled materials that are used. This demonstrated a potential route of exploiting spin filtering effects in non-magnetic semiconductors.

In addition to this experimental work, simulations of these spin sensitive signals have been performed using a classical billiard ball model, which included both spin precession and a spin-dependent electron energy. These simulations used an iterative approach to entwine the spin and orbital motion, and as such required a conservation of energy approximation. In this paper, we compare this simple model with the results of a fully entwined semi-classical approach which does not include this energy approximation. We have also incorporated into the model the effects of electrical gates by including a spatially varying Rashba interaction, which would make possible fast control of spin. We will present the results of these new simulations, including a discussion how they compare to experimental measurements and the potential for new device designs.

8813-105, Session 21

High-performance spintronic computing with magnetoresistive semiconductor heterojunctions *(Invited Paper)*

Joseph S. Friedman, Northwestern Univ. (United States)

Manipulation of the spin degree of freedom provides an opportunity for substantial improvements in computing efficiency. While spintronic memory is already making its way into consumer products, spintronic logic faces additional challenges. Unlike memory, in which a device needs to have two stable and distinct states, logic has the additional requirement of cascading: the output of each logic gate must be capable of driving the input of several similar logic gates. This feature has proven difficult to implement and a major impediment to the development of spintronic processors.

Two recently invented logic families, spin-diode logic and emitter-coupled spin-transistor logic, provide an opportunity for high-performance cascaded logic circuits. These logic families make use of magnetoresistive semiconductor heterojunctions, in which the presence of a magnetic field causes a major increase in resistance. The state of the device can be controlled through the magnetic field created by a nearby current to perform logical operations. This phenomenon is exploited by placing two control wires alongside a magnetoresistive heterojunction diode or transistor, permitting these control wires to function as logical inputs. The output currents of these devices are connected to the inputs of similar devices to produce cascaded logic circuits.

Spin-diode logic and emitter-coupled spin-transistor logic produce highly compact circuits with superb speed and power characteristics. In particular, circuits realized in these logic families use three to ten times fewer devices than conventional CMOS. Additionally, there is minimal dynamic power dissipation, presenting a pathway for low power high performance computing beyond 10 GHz.

8813-84, Session 22

Spins and pseudospins in graphene *(Invited Paper)*

Roland Winkler, Northern Illinois Univ. (United States); Ulrich Zuelicke, Victoria Univ. of Wellington (New Zealand)

Recently atomically flat layers of carbon known as graphene have become the rising star in spintronics as their electrons carry not only the ordinary spin degree of freedom, but they also have a pseudospin degree of freedom tied to the electrons' orbital motion which could enable new routes for spintronics.

Here we focus on bilayer graphene (BLG). Using group theory we have established a complete description of how electrons in BLG interact with electric and magnetic fields. We show that electrons in BLG experience an unusual type of matter-field interactions where magnetic and electric fields are virtually equivalent: every coupling of an electron's degrees of freedom to a magnetic field is matched by an analogous coupling of the same degrees of freedom to an electric field. This counter-intuitive duality of matter-field interactions allows novel ways to create and manipulate spin and pseudo-spin polarizations via external fields that are not available in other materials.

8813-85, Session 22

Silicene: from epitaxial growth toward technological applicability *(Invited Paper)*

Patrick Vogt, Technische Univ. Berlin (Germany); Andrea Resta, Aix-Marseille Univ. (France) and CINaM - Ctr. Interdisciplinaire de Nanoscience de Marseille (France); Thomas Bruhn, Aix-Marseille Univ. (France) and CINaM - Ctr. Interdisciplinaire de Nanoscience de Marseille (France) and Technische Univ. Berlin (Germany); Paola De Padova, Istituto per lo Studio dei Materiali Nanostrutturati (Italy); Guy Le Lay, Aix-Marseille Univ. (France) and CINaM - Ctr. Interdisciplinaire de Nanoscience de Marseille (France) and Istituto per lo Studio dei Materiali Nanostrutturati (Italy)

Since the discovery of graphene and the tremendous advancement in this field of research enormous efforts have been invested to search for other similar 2-dimensional materials, especially silicene. Silicene, a 2D structure of Si atoms in a honeycomb-like arrangement, shares essentially the same electronic properties as graphene, namely an electronic linear dispersion resembling that of relativistic Dirac fermions. Despite these similarities to graphene, silicene would not only differ in terms of chemical reactivity but tuning of the electronic band gap or spintronic applications, such as spin-filters, have been suggested for gated silicene layers, opening novel applications for these 2D materials.

We could show recently that monolayer epitaxial silicene can be synthesized a silver (111) templates. In this case the atomic structure turns out to be more complex and is influenced by the substrate surface. Meanwhile, other orientations of silicene on Ag(111) and the formation of silicene on another metallic substrate have been discussed in literature.

Based on these results we have grown silicene multilayer structures which can be explained by stacking of single silicene layers. We will discuss the atomic structure and the electronic properties of this layered system and compare the strong similarities of these silicene stacks to graphite.

The formation of silicene multi-layer structure opens new possibilities to solve one puzzling problem for the technological applicability: the exfoliation of stand-alone silicene layers.

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8813-86, Session 22

Spin-valley coupling in atomically thin dichalcogenides *(Invited Paper)*

Xiaodong Cui, The Univ. of Hong Kong (Hong Kong, China)

Motivated by the triumph and limitation of graphene for electronic applications, atomically thin layers of group VI transition metal dichalcogenides are attracting extensive interest as a class of graphene-like semiconductors with a desired band-gap in the visible frequency range. The monolayers feature a valence band spin splitting with opposite sign in the two valleys located at corners of 1st Brillouin zone. This spin-valley coupling, particularly pronounced in tungsten dichalcogenides, can benefit potential spintronics and valleytronics with the important consequences of spin-valley interplay and the suppression of spin and valley relaxations.

Here we report the first optical studies of WS2 and WSe2 monolayers and multilayers. The efficiency of second harmonic generation (SHG) shows a dramatic even-odd oscillation consistent with the presence (absence) of inversion symmetry in even (odd) layer. Photoluminescence (PL) measurements show the crossover from an indirect band gap semiconductor at mutilayers to a direct-gap one at monolayers. The PL spectra and first-principle calculations consistently reveal a spin-valley coupling of 0.4 eV which suppresses interlayer hopping and manifests as a thickness independent splitting pattern at valence band edge near K points. This giant spin-valley coupling, together with the valley dependent physical properties, may lead to rich possibilities for manipulating spin and valley degrees of freedom in these atomically thin 2D materials.

8813-87, Session 22

Optical manipulation and electrical control of valley pseudo-spins in atomically thin semiconductors *(Invited Paper)*

Sanfeng Wu, Xiaodong Xu, Univ. of Washington (United States)

Electronic valleys are energy extrema of Bloch bands in momentum space. Analogous to the electron spin degree of freedom, valley indices can be considered as pseudospins for new modes of electronic and photonic device operation. In this talk we will discuss experimental progress on the investigation of these pseudospins using atomically-thin semiconductors (MoS2, WSe2 etc.), which are either monolayer or bilayer group VI transition metal dichalcogenides. Using MoSe2 as an example, we first show that these new 2D semiconductors exhibit remarkable excitonic effects with a large (30meV) trion binding energy. By applying a gate voltage, we demonstrate the electrostatic tunability of charging effects in positively charged, neutral, and negatively charged excitons via photoluminescence. We further show that these excitons are associated with valley pseudospins and can be addressed by specific light helicity. This demonstration of optical preparation of valley-pseudospins arises from the inversion-symmetry breaking in monolayer samples. Using inversion-symmetric bilayer samples, we are able to investigate the feasibility of on/off switching and continuous tuning of the valley pseudo-spins by breaking the inversion symmetry through vertical gate electric fields. We show that the circularly polarized photoluminescence can be tuned from -15% to 15% as a function of gate voltage and can be well explained as resulting from the continuous variation of valley magnetic moments. Therefore, we show that these new 2D semiconductors not only behave as remarkable excitonic systems, but also provide an ideal platform for realizing the optical manipulation and electrical control of valley degrees of freedom.

8813-88, Session 23

Magnetic field controlled reconfigurable logic gates with integrated nanomagnets *(Invited Paper)*

Mark B. Johnson, U.S. Naval Research Lab. (United States); Jin Dong Song, Korea Institute of Science and Technology (Korea, Republic of); Jinki Hong, Korea Univ. (Korea, Republic of); Joonyeon Chang, Korea Institute of Science and Technology (Korea, Republic of)

We describe the development of a magnetic logic device that is uniquely different from spintronic approaches based on magnetoresistive effects that derive from spin dependent transport of carriers. The core of our device is a thin film avalanche diode channel fabricated as a p-n bilayer. Because of the structural asymmetry, the carriers are sensitive to an in-plane magnetic field and the diode has a large magnetoresistance. We characterize our device as a current switch. The high- and low-current states are well defined and are determined by the magnetic field. A field of constant value and positive or negative orientation is an appropriate selector. We then describe an integrated avalanche diode logic device in which the magnetic field is provided by the local fringe field of a patterned ferromagnetic film with nanometer dimensions. The magnetization orientation of the nanomagnet, and the sign of the magnetic field, is set by spin torque transfer (STT) using small amplitude current pulses. We describe how simple arrangements of these integrated devices can be used as dynamically reconfigurable logic gates. Reconfigurable Boolean AND/OR gates using early prototype structures with micron dimensions are shown. Scaling arguments that justify the plausibility of fabricating an integrated device with dimensions of 100 nm are presented. These arguments suggest that such a device could have current gain, capable of driving STT write processes in spintronic circuits.

8813-89, Session 23

Soft x-ray microscopy: facing the mesoscale challenge in magnetism *(Invited Paper)*

Peter Fischer, Mi-Young Im, Lawrence Berkeley National Lab. (United States)

Over the last decade magnetism research focused on a fundamental understanding and controlling spins on a nanoscale. The next step beyond the nanoscale will be governed by mesoscale phenomena , since they are expected to add complexity and functionality, which are essential design parameters e.g. for the realization of future spintronic devices. The development and application of multidimensional visualization techniques, such as tomographic imaging and the investigations of fast and ultrafast spin dynamics will play key roles in achieving mesoscience goals.

Soft X-ray spectromicroscopy offers the unique combination of high spatial and temporal resolution, elemental specificity, and magnetic sensitivity by using the strong X-ray dichroism effect in the soft x-ray regime as magnetic contrast. Three-dimensional (3D) soft X-ray tomography using Fresnel zone plate based transmission soft x-ray microscopies is routinely used at synchrotron sources but almost exclusively for biological imaging. 3D imaging of magnetic structures is of large interest to understand e.g. interfaces in magnetic multilayers, the inner structure of magnetic nanocrystals, nanowires or the functionality of artificial 3D magnetic nanostructures. In this talk we will discuss the opportunities and limitations of new analytical approaches for magnetic x-ray tomography by presenting first results obtained with a new tomographic setup at the full-field soft x-ray microscope at the Advanced Light Source in Berkeley.

The collaboration with D. Rueffer, A. Fontcuberta i Morral , Th. Schwarze, R. Huber, D. Grundler, D. Makarov, R. Streubel, , J. Lee and S.-K. Kim is highly appreciated.

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8813-90, Session 23

Spin wave logic devices for general and special task data processing *(Invited Paper)*

Alexander Khitun, Univ. of California, Riverside (United States)

Spin wave logic devices constitute a type of magnetic logic exploiting spin waves for information transmission and processing. The utilization of waves for data transmission makes it possible to code logic 0 and 1 in the phase of the propagating wave, use waveguides as passive logic elements for phase modulation and exploit wave interference for achieving logic functionality. In this talk, we describe the current status of spin wave logic devices and present most recent experimental data. We also discuss the possibility of building Boolean and special task data processing circuits exploiting spin waves.

8813-91, Session 23

Magnetic bipolar junctions devices for spin logic applications at room temperature *(Invited Paper)*

Bruce W. Wessels, Northwestern Univ. (United States)

Narrow gap III-V semiconductors have been investigated for semiconductor spintronics. By alloying these semiconductors with manganese, magnetic semiconductors result. Giant magnetoresistance has been observed in narrow gap magnetic semiconductor p-n heterojunctions. The giant magnetoresistance which is positive is attributed to spin selective carrier scattering in the magnetic semiconductor. For a InMnAs/InAs heterojunction diodes a giant magnetoresistance of 2680 % is observed at room temperature. This work indicates that highly spin-polarized magnetic semiconductor heterojunctions can be realized that operate at room temperature. Devices based on the giant magnetoresistance include spin diodes and bipolar magnetic junction transistors. We utilize the diode magnetoresistance states to create a binary spin logic family.

8813-92, Session 24

Theory of electromechanical coupling in dynamical graphene *(Invited Paper)*

Mircea Trif, Pramey Upadhyaya, Yaroslav Tserkovnyak, Univ. of California, Los Angeles (United States)

Graphene has become one of the most remarkable existing materials, hosting a plethora of exotic effects, such as Klein tunneling, the half-integer quantum Hall effect, {it zitterbewegung} etc. All of these effects are consequences of the low-energy Dirac spectrum exhibited by the electronic quasiparticles, even though the underlying theory is nonrelativistic. This two-dimensional (2D) material is embedded in a three-dimensional (3D) space, which allows for large out-of-plane displacements (limited by surface tension and a weak bending rigidity). The electronic properties are sensitive to such mechanical distortions, offering new pathways for controlling both the charge and valley degrees of freedom. In this paper we study the coupling between the Dirac electrons and the time-dependent elastic distortions in graphene, for a general 3D excitation of the lattice. We show, using time-dependent perturbation theory, that the effective gauge field resulting from the electromechanical coupling has four contributions, two of which are quasistatic and the other two being dynamic. The quasistatic gauge field is due to both strain and curvature, while the dynamic gauge field arises due to translations and rotations of the local atomic orbitals, and vanish in the static case. We find that the quasistatic and dynamic gauge fields can become comparable in magnitude for finite frequencies and, in particular, such couplings can be of relevance for valleytronics effects in graphene, as the mechanical fluctuations mediate an indirect coupling between charge and valley degrees of freedom.

8813-93, Session 24

Spin pumping at Permalloy/graphene interfaces *(Invited Paper)*

Enrique del Barco, Simranjeet Singh, Univ. of Central Florida (United States); Ajit Patra, National Univ. of Singapore (Singapore); Brett Barin, Univ. of Central Florida (United States); Barbaros Özyilmaz, National Univ. of Singapore (Singapore)

We present evidence of large spin relaxation effects in CVD graphene observed by means of ferromagnetic resonance (FMR) measurements of Permalloy/graphene (Py/Gr) films. A substantial increase of the FMR linewidth in the Py/Gr film, as compared to the Py film alone, is interpreted in terms of an enhancement of the Gilbert damping in the ferromagnetic layer as a consequence of spin pumping at the Py/Gr interface, which is driven by the Py magnetization dynamics (i.e. precession of the magnetization induced by the microwave stimulus at resonance). The remarkable increase in the FMR linewidth compares with observations in other bilayer systems in where thick layers (thicker than the spin diffusion length) of heavy metals with strong spin-orbit interaction are employed as the non-magnetic layer. Our results indicate that spin relaxation in CVD graphene must be greatly enhanced in order to account for the losses of angular momentum in the ferromagnet. We will also present a comparative study of the Gilbert damping in Py/NM films employing highly ordered pyrolitic graphene as the non-magnetic layer, for which a more moderate broadening of the FMR linewidth is observed.

8813-94, Session 24

Graphene as a spin channel for spintronic based logic *(Invited Paper)*

Abdelmadjid Anane, Bruno Dlubak, Marie-Blandine Martin, Pierre Seneor, Albert Fert, Unité Mixte de Physique CNRS/Thales (France)

Electronic devices based on spin transport will play a major role in future Information and Communication Technologies (ICT), to that respect, they are fully considered in the ITRS road map. Spin information processing requires the ability to inject, manipulate and detect spins. Yet, it was soon understood that this concept will be very difficult to achieve with conventional semiconductors (GaAs or Si).

Here we will present a set of results on an alternative route where the channel is no longer a conventional semiconductor but graphene. Graphene is expected to be a good candidate for spin information transport : its mobility at room temperature outperforms that of any other material and its spin orbit coupling as well as its hyperfine interaction are expected to be very small. Using high quality multilayer graphene grown on SiC wafers together with finely tuned Al2O3 tunnel barrier, we experimentally demonstrate using spin transport experiments in the lateral spin-valve geometry that the spin diffusion length is at least of the order of 100 µm [1]. The spin signal obtained is in the MW range and the spin channel efficiency is as high as 75%. Our results make experimentally relevant theoretical propositions for spin logic devices [2]. An overview of the latest experimental results as well as the theoretical framework governing spin injection in graphene will be presented.

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8813-95, Session 25

Structural optimization of MTJs with a composite free layer *(Invited Paper)*

Alexander Makarov, Viktor A. Sverdlov, Siegfried Selberherr, Technische Univ. Wien (Austria)

Magnetoresistive random access memory with spin transfer torque (STT-MRAM) is a promising candidate for future universal memory. However, improvement regarding the essential parameters is still needed. Finding alternative architectures for magnetic tunnel junction (MTJ) structures is of considerable importance for the success of STT-MRAM. A MTJ with a composite free layer (C-MTJ) was proposed in our early work. The free magnetic layer of such a structure consists of two equivalent parts of half-elliptic form separated by a narrow non-magnetic spacer. The C-MTJs demonstrate a substantial decrease of the switching time and switching current as compared to the standard MTJ with the monolithic free layer.

In this work, we perform the structural optimization of C-MTJs by means of extensive micromagnetic simulations and propose a new structure of the composite free layer, C2-MTJ. In a C2-MTJ the free layer consists of the two ellipses with the major axes a/2 and b (a>2b) inscribed into a rectangle a x b. This structure is easier to fabricate as compared to the previous generation of C-MTJs. We investigated the switching statistics depending on the geometry. We find that the new C2-MTJ switches as fast as the previous one, which is 2 times faster than the structure with a monolithic free layer, without loss of thermal stability. The narrow switching time distribution characteristic of C-MTJs is also preserved in C2-MTJs. Therefore, the newly proposed C2-MTJ offers greater potential for performance optimization of STT-MRAM devices.

8813-96, Session 25

Magnetic circular dichroism in (Ga,Mn)As and what it tells us about its band structure *(Invited Paper)*

Margaret Dobrowolska, Xinyu Liu, Jacek K. Furdyna, Univ. of Notre Dame (United States); Mona Berciu, The Univ. of British Columbia (Canada); Kin Man Yu, Wladek Walukiewicz, Lawrence Berkeley National Lab. (United States)

GaMnAs is a ferromagnetic semiconductor that is considered to be an ideal candidate for spintronic applications. However, despite a decade of research, the properties of GaMnAs are still not fully understood, thus preventing strategies for optimizing the preparation procedures of GaMnAs with Curie temperatures sufficiently high for realistic device applications. This talk will address the unresolved issue of ferromagnetism in GaMnAs, focusing on the question of whether the ferromagnetic order in this material is mediated by valence band holes or by holes residing in an impurity band. The results to be presented are based on the study of a wide range of GaMnAs samples, using a comprehensive set of experiments that include magnetic circular dichroism, magnetization, and electrical transport measurements, along with studies of microscopic composition by channeling Rutherford back-scattering and particle-induced x-ray emission. These experiments show unambiguously that the holes underlying ferromagnetic order in GaMnAs reside in the impurity band; and that it is not only the concentration of Mn and of holes that establishes the Curie temperature of this material, but also the specific location of the Fermi level in the impurity band. Since the location of the Fermi level can be controlled by a variety of means both during and after growth, this new understanding automatically leads to important insights and guidelines for increasing the critical temperature of this material.

8813-97, Session 25

Introducing and manipulating magnetic dopant exchange interactions in III-V semiconductor nanowires *(Invited Paper)*

Manu Hegde, Ian D. Hosein, Shokouh S. Farvid, Pavle V. Radovanovic, Univ. of Waterloo (Canada)

Control of electron spins in transition metal-doped semiconductor nanostructures has considerable potential for spintronics. Specifically, diluted magnetic semiconductor nanowires (DMS-NWs) are promising building blocks for the bottom-up assembly of functional devices, and may enable microscopic understanding of the origin of transition-metal dopant spin ordering in semiconductors. However, the control of dilute magnetic interactions has largely been restricted to low temperatures, limiting their potential technological applications.

In this talk I will review our recent work on the synthesis, and spectroscopic and magnetic properties of manganese-doped III-V NWs. Using high-resolution circularly polarized X-ray microscopy imaging we directly showed intrinsic magnetization of manganese dopants in individual GaN NWs at room temperature, and demonstrated the dependence of the manganese exchange interactions on the NW orientation relative to the external magnetic field. The NW anisotropy allows for the control of dilute magnetization in a single NW. A comparison between the single and ensemble NW spectroscopic and magnetic measurements suggests co-deposition of Mn secondary phases alongside nanowires, which can lead to erroneous conclusions about the origin of magnetic ordering. An extension of these measurements to other nanostructured DMS systems will also be discussed. The application of bottom-up approaches, such as in-situ nanowire growth control or targeted positioning of individual NWs, allows for the design of networks for quantum information technologies.

8813-98, Session 25

Imaging spin wave with micro-Brillouin light scattering *(Invited Paper)*

Xiaoqin Li, The Univ. of Texas at Austin (United States)

The continuing demands of advancing information storage and processing technologies have attracted much attention to spin waves in magnetic microstructures. Numerous experiments have demonstrated that spin waves play an important role in the operation of spin torque based memory devices and spin torque nano-oscillators. In addition, several spintronic devices based on propagating spin waves have been proposed, such as the spin wave bus and a Mach Zehnder-type interferometer for performing logic operations. We investigate fundamental properties of spin waves via Micro-Brillouin Light Scattering technique. I will discuss two examples in this presentation. In the first example, we observed a surprising oscillatory behavior when measuring the decay length of spin waves in a Permalloy thin film excited by an asymmetric coplanar antenna. The oscillations can be modeled as the interference between a propagating spin wave and a background magnetization with spatially uniform phase. Calculations suggest that this interference arises from nonlocal characteristics of the magnetization susceptibility and is largely independent of the antenna geometry. In the second example, we demonstrate that magnon spectra can be used as a local temperature sensor. The frequency shift of magnon spectra provides an absolute temperature scale. The capability of characterizing magnon temperature is critical for understanding thermally driven spin transport in magnetic thin films, essential for the emerging field of spin caloritronics.

8813-99, Session 26

Spintronics of weakly spin-orbit coupled semiconductors *(Invited Paper)*

Christoph M. Boehme, The Univ. of Utah (United States)

While the term “Spintronics” was originally introduced as label for technologies that represent information through spin states rather than charge states, it is nowadays oftentimes used solely in the context of spin-polarization, spin-injection, spin-transport and spin-orbit effects. Carbon based semiconductors display only weak spin-orbit coupling and - in the case of organic semiconductors - charge transport via hopping through strongly localized states. These materials appear at first glance therefore to be entirely unsuitable for spintronics. However, they also exhibit spin related effects not seen in materials with strong spin-orbit coupling which can be used for an alternative, different approaches to spintronics based on spin-permutation symmetry states of charge carrier pairs rather than spin-polarization states. Reading spin-permutation symmetry is straight forward when pronounced spin-selection rules exist. In contrast to spin-polarization, permutation symmetry does not depend directly on temperature and magnetic field strength. Furthermore, the absence of spin-orbit coupling can also allow for long spin-coherence times and thus, the possibility to connect spintronics to an all spin based memory which may be applicable to spin-based quantum information concepts. While spin-orbit coupling is needed in traditional spintronics for electric field controlled spin-manipulation, low-spin-orbit coupled devices may achieve the same via electric field controlled spin-exchange interaction. In this talk, our work on the development of this alternative organic spintronics concept will be presented and the state of its experimental implementation will be discussed.

8813-100, Session 26

Measurement of spin-flip scattering time and photon echo response in GaMnAs *(Invited Paper)*

Kimberley C. Hall, Murat Yildirim, Sam A. March, Reuble Mathew, Angela Gamouras, Dalhousie Univ. (Canada); Xinyu Liu, Margaret Dobrowolska, Jacek K. Furdyna, Univ. of Notre Dame (United States)

The III-V diluted magnetic semiconductors (DMS) offer the ability to actively tune ferromagnetic characteristics through control of the hole population using electrical gates or optical excitation, making these materials attractive for a whole host of magneto-sensitive semiconductor devices. Despite this promise, open questions remain regarding the fundamental properties of these materials due to the complex interplay of defect-induced localization and exchange coupling. Here we demonstrate the power and flexibility of femtosecond four-wave mixing spectroscopy for investigating the electronic structure and magnetic properties of DMS. Spectrally-resolved four-wave mixing measurements on GaMnAs indicate that (s,p)-d hybridization leads to optical signatures in the nonlinear emission spectrum consistent with an enhancement in the valence band density of states [1], in agreement with local tight-binding calculations [2]. Direct measurement of the interband dephasing kinetics using time-resolved four-wave mixing provides an upper bound on the time scale for spin-flip scattering between holes and Mn ions of 40 fs [3], providing new insight into exchange coupling in this system. We also show that the interband response exhibits the characteristic signatures of a photon echo, despite the presence of defect-induced band tailing.

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8813-101, Session 26

Giant collective spin-orbit field in quantum wells: fine structure of spin plasmons *(Invited Paper)*

Carsten A. Ullrich, Univ. of Missouri (United States); Irene D'Amico, The Univ. of York (United Kingdom)

Spin-orbit (SO) coupling is a relativistic quantum mechanical effect which contributes to the fine structure splitting of atomic spectral lines. In extended solids, SO coupling causes many important phenomena which can be quite different from the atomic case. For instance, itinerant electrons in doped semiconductors have a distribution of momenta, and each electronic spin precesses in its own momentum-dependent SO field (leading to the D'yakonov-Perel' dephasing of nonequilibrium spin distributions). However, many-body effects can lead to a striking collective reorganization of the SO fields, causing an electronic behavior like in a macroscopic quantum object. Intersubband spin plasmons in quantum wells are subject to a giant collective SO field that splits the spin-plasmon spectrum into a triplet. This theoretically predicted effect [1] is experimentally verified [2] using inelastic light scattering in the presence of magnetic fields for an asymmetrically doped GaAs quantum well. We also demonstrate the same effect for spin waves in a CdMnTe quantum well. These results provide a powerful indication that these constructive phenomena are universal to collective spin excitations of conducting systems. We also demonstrate that spin plasmon damping is dominated by the spin Coulomb drag effect [3].

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8813-102, Session 26

Spins in silicon MOSFETs: electron spin relaxation and hyperpolarization of nuclear spins *(Invited Paper)*

Cheuk Chi Lo, Univ. College London (United Kingdom); Christoph D. Weis, Lawrence Berkeley National Lab. (United States); Johan van Tol, National High Magnetic Field Lab. (United States); Jeffrey Bokor, Univ. of California, Berkeley (United States); Thomas Schenkel, Lawrence Berkeley National Lab. (United States); John J. L. Morton, Univ. College London (United Kingdom)

The spin degree of freedom of both mobile and localized electrons in silicon have extraordinary long spin relaxation times, making silicon an attractive candidate for spintronics applications and quantum information processing. In this talk, we will discuss recent results in measuring the conduction electron spin relaxation and coherence times in silicon MOS systems using electrically detected magnetic resonance. We will also discuss an all-electrical donor nuclear spin polarization method in silicon by exploiting the tunable interaction of donor bound electrons with conduction electrons, and achieve over two orders of magnitude nuclear hyperpolarization at T=5K and B=12T with an in-plane magnetic field. Both nuclear hyperpolarization and antipolarization can be achieved when operating the device in the quantum Hall regime with an out-of-plane magnetic field*. Our results demonstrate that donor nuclear spins can be initialized through local gate control of electrical currents without the need for optical excitation, enabling the implementation of nuclear spin qubit initialization in dense multi-qubit arrays.

*C.C. Lo et al, PRL 110, 057601 (2013)

8813-103, Session 26

Discontinuous envelope function in semiconductor heterostructures *(Invited Paper)*

Henri-Jean Drouhin, Ecole Polytechnique (France); Federico Bottegoni, Politecnico di Milano (Italy); Hoai T. L. Nguyen, Institute of Physics (Viet Nam); Jean-Eric Wegrowe, Ecole Polytechnique (France); Guy Fishman, Univ. Paris-Sud 11 (France)

The notions of probability current and of spin current play central roles when dealing with transport properties. The notion of spin current is

known to be complicated due to the existence of source terms. However, even the notion of probability current raise a number of questions in systems described by an effective Hamiltonian which contains cubic or higher order momentum terms. In previous papers, we have shown that including spin-orbit interaction induces drastic changes in the properties of the related current operators and implies revisiting the boundary conditions satisfied by the wave functions.1-5 We have given a systematic construction of the probability-current operator ˆJ, based on an effective Hamiltonian written as a ˆp-power series expansion and we have proposed an extension of the envelope function technique to comply with current conservation. We have put into light the simple structure of the extra terms. In the present paper, we relate these new current operators to several transport currents involving charge, spin, and angular momentum. We discuss transport properties of model systems in this context and we connect the results to phenomenological thermokinetics descriptions. This provides practical tools which are valuable for spin engineering of heterostructures.

8813-104, Session 26

Multifunctional Mn1.5Ga films with ultrahigh coercivity, giant perpendicular magnetocrystalline anisotropy and large magnetic energy product *(Invited Paper)*

Jianhua Zhao, L. J. Zhu, S. H. Nie, K. K. Meng, D. Pan, H. Z. Zheng, Institute of Semiconductors (China)

Magnetic materials with high coercivity, perpendicular magnetic anisotropy and magnetic energy product have great application potential in ultrahigh-density perpendicular magnetic recording media, high-performance permanent magnets and ferromagnetic electrodes of spintronic devices with high magnetic-noise immunity and thermal stability. Our experiments demonstrate how novel fabrication of epitaxial films of Mn1.5Ga on GaAs can simultaneously achieve desirable tunable perpendicular coercivity, perpendicular magnetocrystalline anisotropy and magnetic energy product, all at room temperature.

Conference 8814: Carbon Nanotubes, Graphene, and Associated Devices VI

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8814-1, Session 1

Development of an analytical bond order potential for C-H-Cu systems

Xiaowang Zhou, Bryan M. Wong, Donald K. Ward, Sandia National Labs., California (United States)

Carbon nanostructures (nanotubes, nanoribbons, and ordered sheets) continue to attract widespread attention due to their unique properties and use in next-generation electronics. The performance of these materials is critically affected by the defects. Unfortunately, the detailed mechanisms of defect formation during nanostructure growth are either unknown or very poorly characterized. Direct molecular dynamics simulation of nanostructure growth provides powerful means to study defect formation from theories without any prior assumptions regarding the defect formation mechanisms. Such simulations, however, are extremely difficult to achieve requiring the interatomic potential used in the simulations to be transferrable, at least qualitatively, to any configurations that can possibly form on the growth surface. Here we describe our recent efforts on developing an analytical order potential for C-H-Cu systems aiming at enabling direct molecular dynamics simulations of graphene growth on Cu substrate through chemical reactions (i.e., the vapor fluxes are composed of various C-H molecules).

8814-3, Session 1

Different techniques for characterizing single-walled carbon nanotube purity

Neslihan Yuca, Zeyneb Camtakan, Nilgün Karatepe, Istanbul Technical Univ. (Turkey)

Single-walled carbon nanotubes (SWCNTs) have exceptional strength and stiffness and high thermal and electrical conductivity, making them promising candidate (or nanomaterials) in numerous applications, including hydrogen storage, probe tips, quantum wires, and electronic devices. However, they often need to be produced with high purity, especially with defined properties and controlled structures, such as length, diameter, chirality, and so forth. Chemical vapor deposition method has been developed to produce CNTs with high yield while it is still very difficult to get carbon nanotubes pure enough. Transition-metal catalysts, fullerenes, graphitic carbon, amorphous carbon, and graphite flakes are the main impurities in carbon nanotubes.

The purpose of this study was to develop a simple purification process for SWCNTs, along with an understanding of the purification process. In addition, uncomplicated analytical methods were sought to screen and compare various purification methods. We demonstrated an easy and optimum method of cleaning SWCNTs and evaluating their purity. The purification method, which employed oxidative heat treatment followed by 6M HNO_3, H_2SO_4, HNO_3:H_2SO_4 and HCl acid reflux for 6h at 120°C and microwave digestion with 1.5M HNO_3 for 0.5h at 210°C, was straightforward, inexpensive, and fairly effective. Also, it was shown that a combination of thermal gravimetric analysis and nuclear techniques such as NAA and XRF as quantitative screening tools and XRD for the structure analysis to determine the relative purity of SWCNTs.

8814-4, Session 1

Carbon nanotube synthesis with different support materials and catalysts

Fatih Gumus, Nilgün Karatepe, Neslihan Yuca, Istanbul Technical Univ. (Turkey)

Having remarkable characteristics, carbon nanotubes (CNTs) have attracted a lot of interest. Their mechanical, electrical, thermal and chemical properties make CNTs suitable for several applications such as electronic devices, hydrogen storage, textile, drug delivery etc. CNTs have been synthesized by various methods, such as arc discharge, laser ablation and catalytic chemical vapor deposition (CCVD). In comparison with the other techniques, CCVD is widely used as it offers a promising route for mass production. High capability of decomposing hydrocarbon formation is desired for the selected catalysts. Therefore, transition metals which are in the nanometer scale are the most effective catalysts. The common transition metals that are being used are Fe, Co, Ni and their binary alloys. The impregnation of the catalysts over the support material has a crucial importance for the CNT production.

In this study, the influence of the support materials on the catalytic activity of metals was investigated. CNTs have been synthesized over alumina (Al_2O_3), silica (SiO_2) and magnesium oxide (MgO) supported Fe, Co, Fe-Co catalysts. Catalyst – support material combinations have been investigated and optimum values for each were compared. Single walled carbon nanotubes (SWCNTs) were produced at 800° C. The duration of synthesis was 30 minutes for all support materials. The synthesized materials were characterized by thermal gravimetric analysis (TGA), Raman spectroscopy and transmission electron microscopy.

In this study, the influence of the support materials on the catalytic activity of metals was investigated. CNTs have been synthesized over alumina (Al_2O_3), silica (SiO_2) and magnesium oxide (MgO) supported Fe, Co, Fe-Co catalysts. Catalyst – support material combinations were investigated and optimum values for each were compared. Single walled carbon nanotubes (SWCNTs) were produced at 800° C, whereas multi walled carbon nanotubes (MWCNTs) were synthesized at 500° C. The duration of synthesis was 30 minutes for all temperatures and support materials. The synthesized materials were characterized by thermal gravimetric analysis (TGA), Raman spectroscopy and transmission electron microscopy.

8814-5, Session 1

Hydrogen and carbon nanotube production via catalytic decomposition of methane

Cansu Deniz, Yalova Univ. (Turkey); Nilgün Karatepe, Istanbul Technical Univ. (Turkey)

Owing to an increasing world population and demands for higher standards of living and better air quality, the future energy demand is expected to increase significantly. Hydrogen is considered as an energy carrier due to its high conversion efficiency and low pollutant emissions. It can be produced from various sources and transformed into electricity and other energy forms with a low pollution.

The catalytic decomposition of hydrocarbon has been seen as a really useful method for production of pure hydrogen and for the environmental concern. The objective of this study was to assess the impact of catalyst composition and processing parameters on CO_x–free hydrogen production and to produce an available solid form of co-product carbon as carbon nanotubes via catalytic decomposition of methane. The optimum experimental conditions for methane decomposition have been investigated. Fe, Co and Ni are used as catalysts (nanomaterials) over different substrates as SiO_2 and MgO to produce hydrogen at optimum temperatures.

8814-6, Session 2

The role of H2 reduction in the growth of single-walled carbon nanotube

Nilgün Karatepe, Neslihan Yuca, Fatih Gumus, Istanbul Technical Univ. (Turkey)

Carbon nanotubes (CNTs) have attracted considerable attention due to their suitability in potential applications. CNTs have high electronic and thermal conductivity and excellent mechanical strength along their axis, which depends on their diameter, length and chirality. The exact growth mechanism of CNTs has been a progressing effort to understand the growth of CNTs. In the synthesis of CNTs it is clear that hydrogen is an essential element having been implicated in a number of surface morphology changes of the catalyst.

In this study we focused on chemical state and morphology of the catalyst which induces growth of SWCNTs directly from iron catalyst on magnesium oxide support material using chemical vapor deposition method . We reported on the effect of hydrogen gas introduced before and/or during the synthesis of SWCNTs. The synthesis conditions were selected as: catalyst calcination temperatures of 500 and 700°C, calcination time of 30 and 45 minutes, hydrogen concentrations of 50 and 100 % vol, synthesis temperature of 800°C and synthesis time of 30 minutes. The synthesized materials were characterized by thermogravimetric analysis (TGA), XRD and XPS. Effect of H2 reduction on catalyst calcination and CNT synthesis were investigated

8814-7, Session 2

Nitrogen doped graphene band gap engineering by chemical vapor deposition

Isaac Ruiz, Wei Wang, Zafer Mutlu, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

Much attention and excitement has revolved around graphene since the University of Manchester first isolated small flakes in 2004. Being the first 2D material ever observed pristine graphene has demonstrated to have remarkable optical, electrical, mechanical and thermal properties that are expected to one day revolutionize science and technology. One unique property is the cone shaped conduction and valence bands that converge at the K points of the Brillouin zone, which give graphene it remarkable mobility values but also zero bandgap. In order to utilize graphene devices to their full potential a band gap needs to be opened and one proposed method of opening a band gap is through doping. Here a one-step process for synthesizing graphene and substitutionally nitrogen doped graphene (N-graphene) by chemical vapor deposition on thin copper foils is presented. It is demonstrated that the doping concentration can be a controlled by varying the dopant gas exposure time during the growth. The doping concentration and doping uniformity is determined by X-ray Photoelectron Spectroscopy (XPS), and is further confirmed by Raman Spectroscopy and Raman Mapping. Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) also determine the uniformity and quality of the prepared graphene samples once transferred on 300nm SiO2/Si substrates. Finally it is shown that by doping graphene, a bandgap can be opened while still having respectable electron mobility by measuring the performance of a graphene MOSFET.

8814-8, Session 2

Industrial metrology of doped graphene sheets

Maziar Ghazinejad, Jennifer Reiber Kyle, Shirui Guo, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

We report the implementation of fluorescence quenching microscopy (FQM) for quick visualization of doping in large regions of graphene. Through reactive ion plasma etching, patterns of p-type graphene, doped with fluorine, are generated. We employ 4-(dicyanomethylene)-2-methyl-6-(4-dimethylaminostyryl)-4H-pyran (DCM) as the fluorescent agent. The emission of DCM is quenched to a different extent by fluorinated and pristine graphene, which provides the fluorescence-imaging contrast essential for this metrology. Fluorescence images of dye-coated graphene distinctly reveal the difference between the doped and as-grown regions. The pristine graphene quenches the DCM emission more efficiently than the fluorinated graphene. Therefore, the regions with pristine graphene appear darker on the fluorescence images than the regions with fluorinated graphene, enabling large-scale mapping of the functionalized regions in CVD grown graphene sheets. Steady-state and time-resolved absorption and emission spectroscopy are used to comparatively characterize the photophysical properties of the dye when immobilized in PMMA films coating bare glass, pristine graphene, and fluorinated graphene. We observe that a three-fold increase in the in the rate constant of non-radiative decay is the principal reason for the DCM fluorescence quenching for the graphene regions of the samples. The spectral overlaps reveal the propensity for energy transfer from DCM to graphene, causing the increase in the rates of non-radiative deactivation of the photo excited dye. Due to its simplicity and consistent results, FQM is now poised for widespread adoption by graphene manufacturers as a basis for facile and high throughput metrology of large-scale graphene sheets.

8814-9, Session 2

Effects of substrate tilt angle and process tube position on graphene layers

Zafer Mutlu, Isaac Ruiz, Hamed Hosseini Bay, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

Graphene, with unique electrical, optical and mechanical properties is a promising material in industrial applications, such as batteries, supercapacitors, transistors and semiconductor devices. These potential applications of graphene have motivated the development of large-scale synthesis of graphene on copper substrates by chemical vapor deposition (CVD). To enable practical applications of large-area, high quality graphene layers at the centimeter and wafer scales, process control needs to be implemented for optimizing the morphology and electrical properties and enable repeatable growth-cycle of graphene layers for process-line implementation. Here we investigate the effects of process tube position and substrate tilt angle on the optical, morphologic and electronic properties of graphene layers. Furthermore, we describe a procedure for process optimization of the growth parameters. Graphene is grown on copper foils or nickel foils by a chemical vapor deposition technique, and transferred to the SiO2/Si and glass substrates. The detailed characterization of the graphene layers are conducted using Raman spectroscopy, optical microscopy (OM), scanning electron microscopy (SEM) and UV-vis spectroscopy. The experimental results show that the position of copper foil into the quartz tube plays a significant role in the Raman features of the graphene, and influences the optical and morphology properties of graphene layers. In addition, the growth process on the tilted copper foils promotes the uniformity of graphene due to geometrical fluidic dynamics. We believe that these results will be useful for determining the optimum processing conditions of high quality graphene layers at the centimeter and wafer scales.

8814-10, Session 2

Large area graphene growth optimization using fluid mechanics

Jeffrey Bell, Univ. of California, Riverside (United States)

Chemical Vapor Deposition (CVD) is a useful method for synthesis of large area graphene sheets. Pulling knowledge from various disciplines of engineering, we investigated a method for optimizing process conditions for large area synthesis of graphene using Fluid Mechanics. Altering the fluid mechanics of the system resulted in shorter growth times yet still achieving the same uniform high quality graphene previously achieved with a standard recipe. The benefit of reducing growth times translates to an industrial scale, allowing for graphene to become produced on a large scale efficiently and timely. Through our experimental procedures, synthesis of uniform, large area graphene could be grown on Cu foil at 1000 C for 3 minutes with a H2 flow rate of 60 sccm, CH4 flow rate of 30 sccm, Argon flow rate of 60 sccm, total pressure of 20 torr and a slow cooling rate of 25 C a minute.

8814-39, Session 2

3D laser micro fabrication of single-wall carbon nanotube/polymer composite microstructures

Shota Ushiba, Satoru Shoji, Kyoko Masui, Osaka Univ. (Japan); Junichiro Kono, Rice Univ. (United States); Satoshi Kawata, Osaka Univ. (Japan)

We demonstrated 3D laser micro fabrication of single-wall carbon nanotube (SWCNT)/polymer composites. Our approach allows one to fabricate three-dimensional SWCNT/polymer composites with a minimum spatial resolution of a few hundreds nm. A near-infrared femtosecond pulsed laser beam was focused onto a SWCNT-dispersed photo resin, and the laser light solidified a nanometric volume of the resin through two photon photopolymerization. The focus spot was three-dimensionally scanned, resulting in the fabrication of arbitrary shapes of the composites. SWCNTs were uniformly distributed throughout the whole structures. We also found that SWCNTs were aligned in polymer nanostructures.

8814-11, Session 3

Sb2Te3-coated multiwalled carbon nanotube arrays for thermoelectric power waves *(Invited Paper)*

Seunghyun Hong, Wonyoung Kim, Seong-Jae Jeon, Seongchu Lim, Hoo-Jeong Lee, Sungkyunkwan Univ. (Korea, Republic of); Seungmin Hyun, Korea Institute of Machinery & Materials (Korea, Republic of); Young Hee Lee, Seunghyun Baik, Sungkyunkwan Univ. (Korea, Republic of)

Multi-walled carbon nanotubes coated by cyclotrimethylene trinitramine (MWCNT/TNA) have recently demonstrated the direct conversion of chemical energy to electricity known as thermoelectric power waves. However, the Seebeck coefficient of carbon nanotubes still needs to be enhanced to produce greater electrical potential. Here we present Sb2Te3-coated MWCNT arrays by a simple sputtering method [1]. By combining Sb2Te3 with a greater Seebeck coefficient, the Seebeck coefficient of the annular multi-shell structure could be enhanced by ~75%. Resultantly, the heterostructure coupled with exothermic chemical reaction of TNA demonstrated an increase in peak electrical potential by 175 % (~198 mV), compared with typical outputs of bare MWCNT/TNA (~72 mV) [1].

[1] Journal of Physical Chemistry C, 2013, 117, 913-917

8814-12, Session 3

Zinc oxide/carbon nanotube based nanocomposite for electrochemical supercapacitors

Badekai Ramachandra Bhat, National Institute of Technology, Karnataka (India); Aravinda L. S. Bhat, National Institute of Technology Karnataka (India); Udaya Bhat, National Institute of Technology, Karnataka (India)

The usage of fossil fuels to meet the demands of energy leading to global warming and resource depletion, hence there is a need for the development of improved methods of energy storing systems and retrieving it whenever we required. Electric double layer capacitors (EDLCs) consisting of carbon based electrode materials like activated carbon, carbon aerogels and carbon nanomaterial in which charge storage is exclusively electrostatic. On the other hand metal oxides and conducting polymers exhibit pseudocapacitance behavior due to fast faradaic process but due to low electrical conductivity of the metal oxides limit its use as supercapacitor electrodes. To overcome this problem, nanocomposites electrode materials for EDLCs and pseudocapacitors have been studied. Various transition metal oxides CNT composites have been studied, out of which Ruthenium oxide (RuO2) based capacitors show high capacitance and high specific power, but due to its high cost and toxicity limit their use. So it is important to develop low cost metal oxide as substitute.

Here in we report a facile route for the synthesis of ZnO decorated carbon nanotubes (CNTs) using Microwave irradiation method. This composite material was investigated for its supercapacitance property in non-aqueous electrolyte. A symmetric double layer super capacitor stack was fabricated by using carbon paper as electrodes. The investigation of the capacitance property of the fabricated super capacitor stack was investigated using cyclic voltammetry, chronopotentiometry and electrical impedance spectroscopy studies. The composite material shows an improved capacitance of 42 Fg-1 compared with the CNTs with better electrochemical reversibility.

8814-13, Session 3

Nanoporous graphene sponge for supercapacitor electrodes

Hamed Hosseini Bay, Wei Wang, Univ. of California, Riverside (United States); Zafer Mutlu, Univ of California, Riverside (United States); Paige Romero, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

Graphene is a unique two dimensional material with exceptional physical and chemical properties. The theoretical surface area of graphene is reported to be 2630 m2g-1, which is significantly higher than activated carbons, graphite and single-walled carbon nanotubes. As a result, graphene and graphene based composite materials have been of great interest for various applications in energy storage/production. Accordingly, owing to its high surface area, graphene is a decent candidate as an electrode in electrochemical supercapacitors. Recent studies indicate that graphene demonstrates the highest capacitance among all carbon-based electrodes for supercapacitors. Moreover the graphene sheets surface is readily accessible by electrolyte. Herein, to increase the capacitance of graphene as well as the power and energy density, a novel porous 3-dimensional graphene-based structure is synthesized by a modified CVD method. In this case, no chemical treatment or activation is necessary and the process is not subjective to particular catalyst substrates. To prepare precursor materials for such structure, a modified sol-gel process has been implemented. Nanostructure samples were characterized by Raman Spectroscopy, Optical Microscopy, Scanning Electron Microscopy, Transmission Electron Microscopy and BET technique. Cyclic voltammetry measurements were also carried out and the results suggest that the use of 3-dimensional nanoporous graphene sponge as electrodes for supercapacitors can be a potential way to achieve enhanced gravimetric capacitance as well as higher energy and power density.

8814-14, Session 4

Supercapacitor electrode based on mixtures of graphite and carbon nanotubes *(Invited Paper)*

Paolo Bondavalli, Thales Research & Technology (France)

This contribution deals with the fabrication of electrodes and supercapacitor cells using a new dynamic air-brush deposition technique. We analyze the effect of mixtures of CNTs and graphite on the electrode and cell properties (energy, power and capacitance) and observe that with a mixture of 75% of graphite and 25% of CNTs, we increase the power by a factor 2.5 compared to bare CNT-based electrodes. This effect is not linked to an increase of the electrodes conductivity, as pointed out in previous papers, but on the mesoporosity of the composites. This is reached thanks to the fact nanotubes tend to act as spacer between the graphite flakes and so enhance the surface but also achieve an optimized mesoporous network. We also analyze the effect of the electrodes' weight first on the capacitance and specific energy and second on the specific power. We report a specific power of 200kW/Kg and a specific energy of 9.1Wh/Kg with electrodes having a surface of 2cm^2 and a weight of 0.25mg composed by 50% of CNTs and graphite (using a common aqueous electrolyte). Our deposition technique delivers supercapacitors with ad-hoc characteristics, by simply modulating the weight and the concentration of the CNT/graphite mixture in a completely reproducible way and with an industrially suitable and low-cost method.

8814-15, Session 4

CNT/PEDOT:PSS nanocomposite based thermoelectric device *(Invited Paper)*

Woochul Kim, Hoon Kim, Sung-Geun Park, Yonsei Univ. (Korea, Republic of)

In this study, PEDOT:PSS which is well-known conducting polymer, and single-walled carbon nanotube which has good electrical conductivity, are used to make a thermoelectric nanocomposite. A novel device architecture was proposed, what we called the spacer-inserted thermoelectric device. Performance of the device was measured and analyzed. The device was used to harvest human body heat. We expect that this new device architecture based on the SWCNT/PEDOT:PSS could be used to recover low quality waste heat recovery.

8814-16, Session 4

Pillared graphene and silicon nanocomposite architecture for anodes of lithium ion batteries

Wei Wang, Isaac Ruiz, Zachary J. Favors, Aaron S. George, Robert Ionescu, Dennis Pleskot, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

In this work, we successfully demonstrated the fabrication of a hybrid carbon-silicon composite nanostructure via using a sputtering evaporation system. Three dimensional pillared graphene nanostructure was grown on metal substrates through a one-step chemical vapor deposition (CVD) by introducing a mixture precursor gases (H2, C2H4). The as-grown carbon nanostructure can be potentially used for the electrodes of energy storage devices such as supercapacitors and battery. We further explored sputtering evaporation system to uniformly deposited a layer of amorphous silicon on the as grown 3D carbon nanostructure. The surface morphologies were investigated by scanning electron microscopy (SEM), transmission electron microscopy (TEM). The results demonstrated relatively homogeneous and densely packed 3D hybrid carbon-silicon nanostructure with a very high porosity. Cyclic voltammetry, charge-discharge, and electrochemical impedance spectroscopy (EIS) are conducted to determine the performance of the 3D hybrid carbon-silicon nanostructure for lithium ion battery anode. The lithium-ion battery based on this hybrid carbon-silicon nanostructure shows a high specific capacity of ~3000 mA h g-1. This hybrid carbon-slicon nanostructure offers a facile and binder-free technique to obtain high capacitive lithium ion battery anodes.

8814-17, Session 4

Covalently functionalized single-walled carbon nanotubes and graphene composite electrodes for pseudocapacitor application

Pierre L. Le Barny, Thales Research & Technology (France); Bernard Servet, Thales Research and Technology (France); Stephane Campidelli, IRAMIS (France); Paolo Bondavalli, Christophe Galindo, Thales Research & Technology (France)

The use of carbon-based materials in electrochemical double-layer supercapacitors (EDLC) is currently being the focus of much research. Even though activated carbon (AC) is currently the state of the art electrode material, AC suffers from some drawbacks including its limited electrical conductivity, the need for a binder to ensure the expected electrode cohesion and its limited accessibility of its pores to solvated ions of the electrolyte. Owing to their unique physical properties, carbon nanotubes (CNTs) or graphene can overcome these drawbacks. It has been demonstrated that high specific capacitance could be obtained when the carbon accessible surface area of the electrode was finely tailored by using graphene combined with other carbonaceous nanoparticles such as CNTs(1).In this work, to further increase the specific capacitance of the electrode, we have covalently grafted onto the surface of single-walled carbon nanotubes (SWCNTs) or graphene oxide (GO), a series of anthraquinone (AQ) derivatives which are electrochemically active materials. The modified SWCNTs (AQ-SWCNT) or GO (AQ-GO) have been characterized by Raman spectroscopy and X-ray photoemission. Then these carbonaceous materials have been transformed into bucky papers by filtration of a solvent nanomaterial suspension, leading to a self-supporting electrode having a pseudocapacitor behavior. We report here for the first time the electrochemical behavior of bucky papers obtained by filtration of mixtures of AQ-SWCNT AQ-GO suspensions.

1) Q. Cheng, J. Tang, J. Ma, H. Zhang, N. Shinya and L.-C. Qin, Phys. Chem; Chem; Phys., 13, 17615-17624, (2011)

8814-33, Session PWed

Improvement in photo-induced charge separation utilizing conjugated ZnO quantum dots and carbon nanomaterials

Dong Ick Son, Won Kook Choi, Korea Institute of Science and Technology (Korea, Republic of)

We report on the successful conjugation of carbon nanomaterials on the surface of ZnO quantum dots (QD) and their application in multi-layer structured ultraviolet (UV) photovoltaic (PV) devices. In situ growth of carbon nanomaterials on the surface of ZnO QDs with a core-shell structure was realized via a mild solution-process method, which resulted in an improvement in photo-induced charge separation and transport of carriers to the collecting electrodes in a fabricated device. The conjugation of the C60 to ZnO QDs or graphene to ZnO QDs leads to a PL quenching of about 71% and 99%, which can be attributed to an efficient transfer of photo-induced electrons from the ZnO QDs to the C60 or from the ZnO QDs to the graphene through a Zn-O-C chemical bonding.

8814-34, Session PWed

Simulation of Au particle interaction on graphene sheets

Angus R. Mcleod, Queensland Univ. of Technology (Australia) and Commonwealth Scientific and Industrial Research Organisation (Australia); Kristy C. Vernon, Queensland Univ. of Technology (Australia); Amanda E. Rider, Kostya Ostrikov, Commonwealth Scientific and Industrial Research Organisation (Australia) and The Univ. of Sydney (Australia)

The interaction of Au particles with few layer Graphene is of interest for the formation of the next generation of sensing devices (Rider, Kumar et al. 2012). In this project we investigate the coupling of single gold nanoparticles to a Graphene sheet, and multiple gold Nanoparticles with a Graphene sheet using COMSOL Multiphysics. By using these simulations we are able to determine the electric field strength and

associated hot-spots for various gold Nanoparticle-Graphene systems. The Au Nanoparticles were modelled as 8nm diameter spheres on a 1.5nm thick (5 layers) Graphene, with properties of Graphene obtained from the refractive index data from (Weber, Calado et al. 2010) and the Au refractive index data from Palik.

The field was incident along the plane of the sheet with polarisation tested for both s and p. The study showed little interaction between the Au and Graphene itself with limited evidence of coupling; however the double particle case where the Graphene sheet separated two Au nanoparticles showed distinct interaction between the particles and graphene. An offset was introduced (up to 4nm) resulting in much reduced coupling between the opposed particles as the distance apart increased. Findings currently suggest that the Graphene layer has limited interaction with incident fields with a single particle present whilst reducing the coupling region to a very fine area when opposing particles are involved. It is hoped that the results of this research will provide insight into Graphene-Plasmon interactions and spur the development of the next generation of sensing devices.

8814-36, Session PWed

Graphene-doped zinc oxide gas sensor

Kanika Anand, Ravi Chand Singh, Guru Nanak Dev Univ. (India); Manmeet Pal Singh, Khalsa College of Engineering & Technology (India)

In this work we have fabricated thick film gas sensors based on graphene doped zinc oxide. The samples were synthesized by in situ reduction of graphene oxide with the formation of zinc oxide nanostructures. Gas sensing properties of the synthesized samples have been investigated at different operating temperatures and gas concentrations. The results indicate that the graphene doped zinc oxide exhibits high sensitivity. Formation of p-n heterojunctions were proposed as the sensing mechanism underlying the enhanced sensitivity of this hybridized gas sensor. Photoluminescence study was performed to find potential application as photoelectric material. The X-ray diffraction (XRD) and field emission scanning electron microscopy (FESEM) were also done for morphological investigations.

8814-37, Session PWed

Boron-doped graphene by chemical vapor deposition

Isaac Ruiz, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

Graphene has stimulated a vast amount of research into 2D materials due to the unique properties graphene has been able to demonstrate. Although new 2D materials such as h-Boron Nitride are beginning to capture much attention, graphene still has much room for research. One important aspect to consider in order further reveal the full applicable potential of graphene is the effects of substitutional doping of graphene. Although there has been much study of nitrogen doped graphene by various methods including, chemical, plasma and epitaxial, there has not been an extensive study of the affect of boron doped graphene. In this study the first synthesis of p type Boron doped graphene by chemical vapor deposition using boron trichloride as a precursor gas. The substitutionally boron doped graphene is confirmed by X-ray photoelectron spectroscopy. The affects of different boron concentrations on the Raman spectra of graphene are studied. Conductive atomic force microscopy is also use to demonstrate the presence and affects of the boron doping.

8814-38, Session PWed

Sodium manganese oxide nanowires for high stability sodium ion battery cathode

Robert Ionescu, Wei Wang, Univ. of California, Riverside (United States)

As the society tends to move towards more efficient and low cost energy resources, a new way of achieving relatively low cost energy storage will be to change our Li-ion battery dependency to a more friendly and abundant resource such as Sodium. Sodium ion batteries will be a new approach of achieving low cost energy storage applications. In this work, an innovative NaxMnyO2 compound nanowire was produced though a hydrothermal process and the as-synthesized nanowires can be used as a cathode material for sodium storage. Hallow carbon nanotubes are introduced in the system as an anode material. Cyclic voltammetry, charge-discharge, and electrochemical impedance spectroscopy (EIS) are conducted to determine the performance of the NaxMnyO2 compound nanowire for sodium ion battery cathode. The sodium-ion battery based on this innovative NaxMnyO2 compound nanostructure shows a high specific capacity with long cycling stability.

8814-18, Session 5

Selective detection of homemade TATP and precursors with CNTFET arrays *(Invited Paper)*

Gilles A. Feugnet, Paolo Bondavalli, Thales Research & Technology (France); Fabrice Pardo, Lab. de Photonique et de Nanostructures (France); Céline Frenois, Commissariat à l'Énergie Atomique (France)

This paper deals with the demonstration of low cost Carbon Nanotube Field Effect transistors (CNTFETs) for TATP and precursor detection. Such devices exploit the extremely sensitive change of the Schottky barrier heights between carbon nanotubes (CNTs) and drain/source metal electrodes. Indeed the main effect is related the gas adsorption creating an interfacial dipole that modifies the metal work function and so the bending and the height of the Schottky barrier at the contacts with the CNTs. This change is strictly dependent of the metal/CNTs junction and of the gas involved. Thus to reach sufficient selectivity, the sensor includes on the same chip an array of 4 CNTFETs composed of 4 different metals (Pd, Pt, Au, Ti) leading to the measurement of a very specific sort of electronics fingerprinting. We will expose results obtained when such sensors are exposed to vapor of TATP, peroxide as well as interferent such a toluene or home-care cleaning product.

8814-19, Session 5

Humidity and temperature investigation in electrical transport properties through random multi-walled carbon-nanotubes networks *(Invited Paper)*

Ibtissem Oueriemi, Univ. Catholique de Louvain (Belgium)

Due to their high surface area to volume ratio, carbon nanotubes (CNTs) have been extensively investigated to enhance the sensitivity of humidity sensors. In this work, multi-walled carbon nanotubes (MWCNTs) were randomly deposited in gaps of microstrip interdigitated capacitive (IDC) structure. I-V measurements and RF characteristics were performed. These experimental results clearly demonstrate the non-linear behaviour of the MWCNTs films. Furthermore, we show that the temperature and humidity have a tremendous impact on the electrical transport in multi-walled carbon nanotubes (MWCNTs) networks. The resistance increases with relative humidity from 30% to 95%. The humidity sensing mechanisms are discussed. The carbon nanotubes junctions may play a more important role in the overall resistance change for water molecule

absorption. The temperature effect of the CNT films on resistance changes cannot be neglected.

The environment sensitivity of carbon nanotubes network indicate it promise as a kind of Humidity and Temperature sensitive material. This study is of importance to master and explore the non-linear behaviour and the environment sensitivity for new potential applications of CNT-based electronic devices.

8814-20, Session 5

Current transport in graphene tunnel field effect transistor under constant electric field

M. S. Fahad, Ashok Srivastava, Louisiana State Univ. (United States); Ashwani K. Sharma, Clay Mayberry, Air Force Research Lab. (United States)

In this work, two different current transport mechanism of graphene tunnel FETs considering constant and variable electric fields are proposed and corresponding I-V characteristics are obtained. The constant electric field model is based on tunneling mechanism of Esaki tunnel diode. The variable electric field model exhibits nearly a linear I-V characteristic of a p-channel graphene T-FET. Contrary to a variable electrical field, constant field model exhibits both resistive and saturation regions of operation characterizing n- and p-channel graphene T-FETs. Effect of oxide thickness on GNR T-EFT performance is also discussed. The performance of GNR T-FET under the constant electric field model is compared with the ITRS projected 2016 MOSFET model and found that the proposed model exhibits seven times lower power and eight times higher intrinsic speed in the upper GHz range. Such high performance makes graphene tunnel FET extremely suitable for design of ultra-low power RF integrated circuits.

8814-21, Session 6

Characteristic study of CNTs and graphene using terahertz time domain and continuous wave spectroscopy *(Invited Paper)*

Horacio Lamela Rivera, Sujitha Puthukodan, Ehsan Dadrasnia, Univ. Carlos III de Madrid (Spain); Dong-Mok Lee, Seunghyun Baik, Sungkyunkwan Univ. (Korea, Republic of); Guillaume Ducournau, Jean-François Lampin, Univ. des Sciences et Technologies de Lille (France); Mohan-Babu Kuppam, Frédéric Garet, Jean-Louis Coutaz, IMEP-LAHC (France)

Carbon nanotubes (CNTs) and graphene have been considered as alternative materials for Indium-Tin Oxide (ITO) as flexible, transparent, and high conductance devices because of unique electrical, optical and mechanical properties (Z. Wu et al., 2004). CNTs and graphene have been applied for electronic devices such as touch screens (S.Bae et al., 2010), conductive flexible adhesives (R.Ma et al., 2012), and field-effect transistor (Y. Lee et al., 2010). In order to suggest electronic applications of carbon nanostructures, it is essential to evaluate electrical and optical properties more accurately with noncontact method.

Many materials that are opaque to visible and infrared light are transparent to THz radiation . As a result, Terahertz spectroscopy has become an important method in studying CNTs and graphene(C. Kang et al., 2004). The parameters of these nanostructures have characteristic resonant frequencies within THz range which is another advantage. Of the many techniques related to THz spectroscopy, Terahertz time domain spectroscopy (THz- TDS) is one of the common methods under study (Y. Ueno et al, 2008).

THz-TDS technique has been intensively used to study the properties of carbon nanostructures thin-films (Kang et al., 2004, Jung et al., 2010, H. Lamela et al., 2011). We have already reported the noncontact and nondestructive THz-TDS tool at high frequencies to get insight of the DC conductivity values for multi-walled carbon nanotubes (MWNTs) thin-film (H. Lamela et al., 2012).

In this work, the characteristics of MWNTs and graphene are explored using a combination of two different THz spectroscopy techniques. Physical modeling and extracted measurement data will be demonstrated for the terahertz and sub-terahertz regimes using TDS in the range of 100 GHz–2 THz and continuous wave (CW) in the range of 325 GHz-500 GHz, respectively.

8814-22, Session 6

Graphene nanomesh gas sensors with sub-10 nm neck size by block copolymer lithography directly on graphene surfaces

Aaron S. George, Isaac Ruiz, Wei Wang, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

The opening of a bandgap in graphene has been observed by etching graphene into nanoscale laterally confined sheets, or graphene nanoribbons. Although graphene nanoribbons with widths of less than 10 nm have shown substantial ON/OFF ratios, the current and conductance of individual graphene nanoribbons is far too low for practical applications. To obtain higher currents in field effect transistors a network of graphene nanoribbons, or graphene nanomesh, should be utilized. We present a scalable method by the ordering of poly(styrene)-block-poly(4-vinylpyridine) block copolymer templates directly on top of chemical vapor deposited graphene. Our technique is advantageous due to multiple reasons. First, we avoid the use of toxic gases (SF6, CHF3, CF4) and HF which have been used in many previous works and may cause defects in the SiO2 layer, effecting device performance. Second, we reduce the number of processing steps and the necessity for any interface materials. Third, is superior control over graphene neck sizes due to the choice and position of the block copolymer etching mask template directly on top of graphene. The graphene nanomesh morphology is demonstrated as a highly sensitive gas sensor due to the ability of molecules to bind at broken graphene edges and the high surface area to volume ratio.

8814-23, Session 6

Transformation of the electrical characteristics of graphene field-effect transistors with fluoropolymer

Taejun Ha, Ananth Dodabalapur, Deji Akinwande, Jongho Lee, Peter Rossky, The Univ. of Texas at Austin (United States)

We report on the improvement of the electronic characteristics of monolayer graphene field-effect transistors (FETs) by an interacting capping layer of a suitable fluoropolymer. Capping of monolayer graphene FETs with CYTOP® improved the on-off current ratio by up to a factor of 2 as well as increased the field-effect mobility also by as much as a factor of two compared to plain graphene FETs. Favorable shifts in the Dirac voltage toward zero with shift magnitudes in excess of 60 V are observed. The residual carrier concentration is reduced to ~2.8x1011 cm-2. Removal of the fluoropolymer from graphene FETs results in a return to the initial electronic properties before depositing CYTOP®. This suggests that weak, reversible electronic perturbation of graphene by the fluoropolymer favorably tune the electrical characteristics of graphene, and we hypothesize that the origin of this improvement is in the strongly polar nature of the C-F chemical bond to self-organize upon heat treatment. We demonstrate a general method to favorably restore or transform the electrical characteristics of graphene FETs which will open up new applications.

8814-24, Session 6

Nonvolatile memories based on graphene related materials: state of the art

Paolo Bondavalli, Thales Research & Technology (France)

The interest for graphitic layers for the fabrication of non-volatile resistive memories (memresistive –like memories) is quite recent. This interest has been outlined also in the 2011 ITRS chapter concerning Emerging Research Devices (i.e. ERD) and more specifically memory devices where ultrathin graphite layers are mentioned as interesting materials for macromolecular memories thanks to the potential fabrication costs that are considered as the primary driver for this type of memory. In this contribution we will present all the major works concerning graphitic memories based on graphene, GO and R-GO exploiting planar and vertical configurations. We will to explain the physics phenomenon behind the nonvolatile resistive effect and to give an overview of the pros and cons of this kind of materials for nonvolatile memories also considering the potential applications related to flexible electronics.

8814-25, Session 6

Single molecule sensing with carbon nanotube devices

Philip G. Collins, Yongki Choi, Gregory A. Weiss, Univ. of California, Irvine (United States)

Nanoscale electronic devices like field-effect transistors have long promised to provide sensitive, label-free detection of biomolecules. In particular, single-walled carbon nanotubes have the requisite sensitivity to detect single molecule events, and have sufficient bandwidth to directly monitor single molecule dynamics in real time. Recent measurements have demonstrated this premise by monitoring the dynamic, single-molecule processivity of three different enzymes: lysozyme (1), protein Kinase A (2), and the Klenow fragment of DNA polymerase I (3). The recordings resolve tens of thousands of individual chemical events, providing excellent statistics as well as insight into rare transitions to chemically-inactive conformations.

1. Y. Choi, et. al., “Single-Molecule Lysozyme Dynamics Monitored by an Electronic Circuit.” Science 335, 319 (2012). Y. Choi, et. al., “Single Molecule Dynamics of Lysozyme Processing Distinguishes Linear and Cross-linked Peptidoglycan Substrates.” JACS 134, 2032 (2012). Y. Choi, et. al., “Dissecting Single-Molecule Signal Transduction in Carbon Nanotube Circuits with Protein Engineering.” Nano Letters 13, 625 (2013).

2. P.C. Sims, et. al., “Electronic Measurements of Single-Molecule Processing by protein kinase A.” JACS, in press (2013).

3. T.J. Olsen, et. al., “Electronic Measurements of Single-Molecule Processing by DNA polymerase I (Klenow fragment).” JACS, in press (2013).

8814-26, Session 7

Photoacoustic molecular imaging using carbon nanotubes and its biomedical applications *(Invited Paper)*

Adam de la Zerda, Stanford Univ. (United States)

Many cancer-specific biomolecules are dynamic in space, time and local environments. Hence, in order to truly understand their role in cancer progression, it is important to visualize them in living subjects – their most natural environment. In this invited talk, I will show how we utilize the ‘photoacoustic effect’ - the conversion of short light pulses into ultrasound waves, for performing highly sensitive disease detection in a living body. By measuring the ultrasound waves emanating from the body, one can create a detailed 3D image of the blood vessels structure, oxygen saturation levels and track external contrast agent molecules as they target diseased tissues such as cancer. I will present our experimental photoacoustic imaging system and the customized carbon nanotube-based nanoparticle agents we synthesized. Specifically, we have recently synthesized a family of carbon nanotubes conjugated to a variety of optical dyes to greatly enhance their photoacoustic properties. We will review a number of in vivo molecular assays we performed using this technology in cancer and eye diseases. Finally, I will present our work on a multi-modality nanoparticle technology that can visualize and guide the resection of a brain tumor along its true margins, including the tumor’s finger-like protrusions that extend into the healthy brain.

8814-27, Session 7

Theoretical investigation of graphene-based waveguide integrated photonic and plasmonic modulators

Jacek Gosciniak, Singapore Univ. of Technology & Design (Singapore)

Theoretical investigations of graphene-based electro-optic plasmonic and photonic modulators will be analyzed and the results will be presented. The effect of different ridge materials and different spacer dielectrics is analyzed showing that a 3 dB modulation with 65 nm-long waveguide is possible with dielectric-loaded surface plasmon polariton waveguides (DLSPPWs) resulting in an energy per bit only 0.08 fJ/bit. The figure of merit defined as the ratio between an extinction ratio and insertion loss was found to be about 5.2 with a low refractive index ridge and increases to over 17.3 for a high refractive index Si ridge compared to 3.5 calculated and measured with photonic graphene-based waveguides. Additionally, it is shown that further improvement in terms of a figure of merit is possible with the rib photonic waveguides with a double-layer graphene placed between slab and a ridge where it is calculated to exceed 250! For such photonic waveguides, a 3 dB modulation is achieved with 6 ?m-long waveguides with the energy per bit of 0.3 fJ/bit. Additionally, the wavelength dependence of the graphene sheet was analyzed showing a redshift with increasing chemical potential what influences on the attenuation of the waveguide which redshifts as well – increasing a gate voltage applied across a graphene layer shifts the attenuation curve to the shorter wavelengths with a 3 dB modulation bandwidth exceeding 15 THz for a 12 ?m-long DLSPP waveguide.

8814-28, Session 7

Long-range surface plasmon polariton detection with graphene field-effect transistor

Ho-Seok Ee, Jinhyung Kim, Chun-Ho Lee, KAIST (Korea, Republic of); You-Shin No, Hong-Gyu Park, Korea Univ. (Korea, Republic of); Min-Kyo Seo, KAIST (Korea, Republic of)

Plasmonic nano-circuits would interface with similar-speed photonic devices and with similar-size electronic components. For a seamless integration, it is required to convert surface plasmon polariton (SPP) signals to electrical signals by an ultra-compact SPP detector. In this study, we demonstrate direct detection of surface plasmon polaritons (SPPs) propagating on a silver nanowire by employing a graphene field-effect transistor (FET). One end of the nanowire is coupled to the grapheme FET channel and the other end is open to the free-space light injection for SPP excitation. The scanning photocurrent imaging technique showed that photocurrents are successfully generated in the graphene FET from long-range SPPs launched by a 660-nm laser incidence. By measuring the dependence of the photocurrent on the incident light polarization, we confirmed that the currents are generated by propagating SPPs, which is excited by coupling of incident laser at opposite end of the nanowire. When a laser beam of ~0.5 mW was incident on the nanowire free-end, a photocurrent of ~0.5 nA is detected even without any bias. Surprisingly, it is one fourth of the photocurrent generated when the pump laser is directly incident on the graphene FET. Considering the conversion efficiency of the pump laser into SPP modes at the nanowire free-end is about a few percent, estimated external quantum efficiency of our device is ~10^-5 at zero-bias. We believe that SPP detectors based on graphene FETs would be a tailored solution to high-speed and broadband detection components for plasmonic nano-circuitry.

8814-29, Session 8

Coherent control of photocurrent in molecular nanojunctions with graphene contacts

Boris D. Fainberg, Holon Institute of Technology (Israel)

The optical response of nanoscale molecular junctions has been the topic of growing experimental and theoretical interest in recent years, fueled by both the rapid advance of the experimental technology and the premise for long range applications. We consider a new kind of graphene-molecule-graphene junctions [1] that exhibit a large conductance and are potentially useful as electronic and optoelectronic devices. The junction consists of a conjugated molecule connecting two parallel graphene sheets and is excited by an electromagnetic field of frequency w polarized in the plane of the graphene sheets. We have studied the photon assisted tunnelling in graphene-molecule-graphene junctions under electromagnetic excitation of electrons and holes in the graphene contacts. Due to their massless energy spectrum [2], graphene electrodes exhibit strongly non-linear electromagnetic response that leads to unique properties of the photon assisted tunnelling in graphene-molecule-graphene junctions. The system shows a slow falling down current evaluated at side-band energies ~ nhw with harmonics index n (~ 1/n^2) in comparison to nanojunctions with metallic leads (~ (J_n)^2, according to famous Tien-Gordon model [3]) where J_n denotes the n-th order Bessel function of the first kind. We also predict the effect of coherent destruction of tunneling in graphene-molecule-graphene junctions. Our results illustrate the potential of graphene contacts in coherent control of photocurrent.

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2. A.H. Castro Neto, F. Guinea, N.M.R. Peres, K.S. Novoselov, A.K. Geim, Rev. Mod. Phys. 81, 109 (2009).

3. R.K. Tien, J.P.Gordon, Phys. Rev. 120, 647 (1963).

8814-30, Session 8

Nonlinear optical properties characterization of semiconducting and metallic single-wall carbon nanotubes

Antonio Carlos Brandão-Silva, Univ. Federal de Alagoas (Brazil); Rogério Lima, Univ. Federal de Minas Gerais (Brazil); Márcio A. R. C. Alencar, UFAL (Brazil); Jandir M. Hickmann, Univ. Federal de Alagoas (Brazil); Cristiano Fantini, Marcos Pimenta, Univ. Federal de Minas Gerais (Brazil); Eduardo J. da Silva Fonseca, Univ. Federal de Alagoas (Brazil)

Single-wall carbon nanotubes (SWNTs) are among the most promising materials aiming the development of new devices. Due to its peculiar physical and chemical properties, they have been exploited in different fields, from nanoelectronics to optics and photonics. Nowadays, it is possible to separate metallic from semiconducting SWNTs, opening new research frontiers and the design of novel applications.

In this work, we characterized the third-order nonlinear optical responses of the samples containing SWNTs separated by its electronic properties, i. e., semiconducting and metallic carbon nanotubes, using the Z-scan technique with thermal management.

Semiconducting and metallic SWNTs samples were separated by gel chromatography method and characterized by Raman and optical absorption spectroscopies. The investigated samples present metallic or semiconducting nanotubes with more than 90% purity and diameter distributions equal to 0.89-1.18 nm for metallic and 0.67-0.83 nm for semiconducting SWNTs. The concentration of nanotubes in each sample was 7.85 x 10-3 mg/ml and 8.53 x 10-3 mg/ml for metallic and semiconducting, respectively.

The nonlinear optical characterization was performed using, as the light source, a pulsed Ti:Sapphire laser, delivering pulses of 200 fs, linearly polarized, with 76 MHZ repetition rate. The measurements were carried out varying the laser wavelength in the range of 755 to 825 nm. It was observed that both systems present large negative nonlinear refractive indexes values, about 10-14 cm2/W, with a strong resonance around 800 nm, but negligible nonlinear absorption in this wavelength length.

Our results indicate that both SWNTs kinds are promising materials for ultrafast nonlinear optical applications.

8814-31, Session 8

Investigation of carbon nanotubes used for the transparent electrode in organic solar cells

Osman Urper, Zeynep Dalkilic, Nilgün Karatepe, Istanbul Technical Univ. (Turkey)

Solar energy is more environmentally friendly energy source compared to traditional energy sources (fossil fuels, nuclear, coals, etc.) due to no carbon dioxide emission or hazardous wastes for this technology. Unfortunately, high costs and low efficiencies are still problem for its applications. Organic solar cells are being pursued as a viable alternative to inorganic devices due to low cost, flexibility and scale-up production. Transparent electrode in organic cells allows the light to pass through to the active material and act as an ohmic contact. Indium-tin oxide (ITO) is currently used in solar cells due to its high conductivity and transparency. However, ITO is expensive in fabrication and also mechanically brittle, which increases the costs and limits the flexibility of devices. In recent years, several transparent electrode materials are used instead of ITO. Among these materials, carbon nanotubes (CNT), is a good alternative having with its unique features such as optical transmissions, electrical and flexibility properties.

The aim of the study is the production of carbon nanotubes by the chemical vapor deposition method, removal of CNT's impurities and the use of obtained single and multi-walled carbon nanotubes as a transparent electrode in organic solar cells. For this purpose, firstly, single-and multi-walled carbon nanotube films as a transparent material, secondly, PEDOT:PSS as hole conductor, and thirdly, P3HT: PCBM as a donor- acceptor were coated on glass substrates. Lastly, the solar cells were obtained with the aluminum coating. The efficiency, fill factor, permeability and other properties of organic solar cells obtained in different conditions were determined in detail.

8814-32, Session 8

Towards graphene photonics and plasmonics

Shin Mou, Don C. Abeysinghe, Joshua Myers, Gail J. Brown, William C. Mitchel, Nima Nader, Justin W. Cleary, Joshua R. Hendrickson, Air Force Research Lab. (United States); Kuei-Hsien Chen, Academia Sinica (Taiwan); Li-Chyong Chen, National Taiwan Univ. (Taiwan); Christian W. Smith, Masahiro Ishigami, Univ. of Central Florida (United States)

Graphene has remarkable optical properties that it is highly transparent while owning large optical absorption coefficient. However, from an optical sensing point of view, it is less attractive due to the low interband optical absorbance resulting from its thinness. An alternative method to achieve optical absorption/ sensing is to utilize the tunable resonant absorption by plasmons in the two-dimensional electron gas (2DEG) of grating-gated field effect transistors (FETs), which is known for a variety of semiconductor systems, giving promise of frequency-agile Infrared/ THz image sensors and spectrometers. Graphene-based plasmonics shows highly tunable and sharp plasmon THz resonance at room temperature while all other semiconductor 2DEG systems generally have plasmon resonance at much lower temperatures (< 77 K.) In addition, graphene has the capability to operate at higher frequencies (shorter wavelength in mid-infrared) due to higher sheet carrier density. As a result, graphene grating-gated detectors have the potential to be the next-generation frequency-agile infrared detectors. We investigate the dc transport of both CVD graphene (grown on Cu) and epitaxial graphene (grown on SiC) with Hall measurement, by which we obtain important parameters such as Hall mobility and sheet carrier density helping us estimate the plasmon resonance frequency and the absorption spectrum. Furthermore, to complement the dc transport characterization, optical transmission/reflection measurements are carried out in Fourier transform infrared spectrometers (FTIRs) to obtain the infrared ac conductance. From that, the carrier density, carrier mobility, sheet resistivity, intraband scattering rate, and graphene layer number can be inferred. Last, we observe graphene plasmon resonances in far-infrared (~ 100 cm-1) by optical transmission measurements through graphene ribbon grating structures.

8815-1, Session 1

Imaging the non-fluorescent materials in living cells *(Invited Paper)*

YanYi Huang, Peking Univ. (China)

Optical probes for live cell imaging are valuable tools in biomedical researches. The inside of a living cell is a rather complex biochemical environment, making it difficult to choose suitable probes that are both highly specific and biochemically inert. Numerous types of nanoparticles, including quantum dots, carbon nanotubes, and metallic nanorods, have been developed as optical imaging probes. Some nanoparticle probes are intrinsically fluorescent, however, many are not. We directly observe the non-fluorescent nanomaterials in living cells using stimulated Raman scattering and transient absorption microscopies. These label-free technologies provide new modalities to study the dynamic behavior of nanomaterials inside the cells with intrinsic three-dimensional imaging capability.

8815-2, Session 1

Orientational imaging of single molecules in polymers *(Invited Paper)*

Zouheir Sekkat, Moroccan Foundation for Advanced Science, Innovation and Research (Morocco)

I discuss the experimental determination of 3 dimentional; 3d; dipole orientations of single fluorescence molecules by using both azimuthal and radial polarizations. I report on the determination of the 3d absorption dipole orientation of single DiI molecules embedded in polymethylmethacrylate (PMMA) films. Theoretical calculations of the electric field distributions created by a focused radially and azimuthally polarized laser beam in the presence of the interface between air and a polymer, shows that the fluorescence intensity is strongly dependent on the depth position of the molecule and that the variation of fluorescence intensity in radial polarization is considerably larger than the one in azimuthal polarization. These findings were confirmed by comparing experimental results using different film thicknesses with theoretically calculated electric field distributions.

8815-3, Session 1

In vivo photoacoustic imaging of breast cancer tumors with HER2-targeted nanodiamonds

Ti Zhang, Huizhong Cui, The Univ. of Kansas (United States); Chia-Yi Fang, Huan-Cheng Chang, Academia Sinica (Taiwan); Xinmai Yang, M. Laird Forrest, The Univ. of Kansas (United States)

Radiation-damaged nanodiamonds (DNDs) are ideal optical contrast agents for photoacoustic (PA) imaging in biological tissues due to their good biocompatibility and high optical absorbance in the near-infrared (NIR) range. Acid treated DNDs were oxidized to form carboxyl groups on the surface, functionalized with polyethylene glycol (PEG) and HER2 targeting ligand for breast cancer tumor imaging. Because of the specific binding of the ligand conjugated DNDs to the HER2-overexpressing murine breast cancer cells (4T1.2 neu), the tumor tissues were significantly delineated from the surrounding normal tissue at wavelength of 820 nm under the PA imaging modality. Moreover, HER2 targeted DNDs result in higher accumulation in tumors as compared to non-targeted DNDs after intravenous injection (i.v.). This demonstrates that targeting moiety conjugated DNDs have great potential for the sensitive detection of cancer tumors and provide an attractive delivery strategy for anti-cancer drugs.

8815-4, Session 1

Deterministic spatio-temporal focusing of light through complex media

Daria Andreoli, Sylvain Gigan, Giorgio Volpe, Ori Katz, Sébastien Popoff, Samuel Gresillon, Institut Langevin (France)

Focusing light in space and time through complex media is paramount in many applied topics in biology, imaging and nanomanipulation. However, light is strongly scattered when propagating through inhomogeneous media, thus preventing the achievement of this goal. Recently, active wavefront shaping techniques have emerged as a powerful way to control light propagation through complex media by relying on the use of spatial light modulators (SLM). The first approaches used phase-conjugation or optimization methods to either spatially focus light and/or to correct for the temporal distortion of an ultrashort pulse after propagating through the scattering medium. An alternative solution to the problem is a matricial approach, where the transmission matrix of the medium is measured. While optimization or phase-conjugation techniques have been shown to allow some degree of temporal control, the matrix approach has been monochromatic so far. Here, we propose to measure and use the transmission matrix to not only focus in space and in time through a complex medium, but to generate an arbitrary spatiotemporal distribution. In essence, we operate a femtosecond laser in CW mode around 800 nm, and measure the monochromatic transmission matrices at several wavelengths that composes the spectrum of the pulse. Once this 3D spatio-spectral matrix is known, we show that it is possible to use only spatial degrees of control on a SLM to deterministically control the pulse propagation through the medium and to focus in space and time at its far side. This approach opens up opportunities to have a full deterministic control of a nano-object through a complex medium.

8815-5, Session 1

Atherosclerotic plaque characterization in apolipoprotein E-deficient mice with micro-Raman spectroscopy and high-frequency acoustic microscopy

Pavlos Anastasiadis, Shiv K. Sharma, Univ. of Hawai'i (United States); Joshua J. Rychak, Targeson, Inc. (United States); John S. Allen III, Univ. of Hawai'i (United States)

Coronary artery disease and its underlying molecular pathology of atherosclerosis are still not completely understood. Murine animal models allow for a more rigorous and systematic way of studying the onset and progression of atherosclerotic plaques than human subjects; however, the associated microscopic size of plaques makes their optical and mechanical characterization a challenging task. This study aims at correlating the biochemical and elastic composition of atheromatous plaque lesions in apolipoprotein E-deficient mouse aorta sections. Near-infrared micro-Raman spectroscopy provides a biochemical characterization of the aorta sections. A complimentary acoustic microscopy study of the same samples determines their elastic properties. Five month old apolipoprotein E-deficient mice on a fat- and cholesterol-rich diet were euthanized in order to excise their aortas. The aorta tissues were sliced using a microtome and kept in -80 °C until investigated with both micro-Raman spectroscopy and acoustic microscopy. Raman spectra were excited by an Invictus 785-nm NIR laser and measured with a fiber-coupled micro-Raman RXN system (Kaiser Optical Systems, Inc., Ann Arbor, MI) equipped with a 785 nm CW laser and CCD detector. The elastic characterization study utilized a high-frequency acoustic microscope (Fraunhofer IBMT, St. Ingbert, Germany) at a center frequency of 100 MHz. The acoustic setup was mounted onto an inverted optical microscope for additional simultaneous optical analysis.

8815-6, Session 1

Observing the growth of single nanoparticles in real time through supercontinuum spectroscopy

Lars O. Herrmann, Jeremy John Baumberg, Univ. of Cambridge (United Kingdom)

A fast scattering spectroscopic technique capturing full broadband spectra with millisecond time resolution enables us to monitor the synthesis or assembly of individual nanoparticles in situ and in real time. Applying this technique for quantitative growth studies of single gold nanorods reveals new information about their growth kinetics. Such experiments open up real time monitoring of chemical reactions at individual nanoparticles as well as new routes towards tailoring nanostructures through opto-chemical feedback.

8815-8, Session 2

Three-dimensional optical nanoscopy with opposing lenses *(Invited Paper)*

Alexander Egner, Laser-Lab. Göttingen e.V. (Germany); Roman Schmidt, Daniel Aquino, Stefan W. Hell, Andreas Schönle, Max-Planck-Institut für Biophysikalische Chemie (Germany); Claudia Geisler, Laser-Lab. Göttingen e.V. (Germany)

Far field optical microscopy is a well established method for the non-invasive 3D-investigation of cellular structures. However, the resolution of conventional light microscopy is limited by diffraction to ~200nm in the focal plane and ~600nm along the optic axis. In order to discern identical labels which are much closer than this, one has to overcome the diffraction barrier.The utilization of optical switching events allows one to circumvent Abbe's diffraction limit: The switching of only markers within an area which is much smaller than the size of a diffraction limited spot to a visible "bright" state while all other markers are switched to a non-visible "dark" state defines a sub-diffraction area. By sequentially recording all areas within the diffraction spot, it is possible to assemble a sub-diffraction image.

The first radical concept for improving the resolution of a far field microscope was Stimulated Emission Depletion (STED) microscopy. In this concept the saturated depletion of the excited state of the fluorescent molecule is used to generate a fluorescent spot that is narrower than the diffraction limit. isoSTED microscopy proved a resolution of up to 21 nm in the lateral and 30 nm in the axial direction, meaning that the resolution is higher by more than an order of magnitude as compared to confocal microscopy.

Another method utilizing molecular switching events for achieving nanoscale resolution in microscopy uses a more pointillist approach. Single molecules which are initially in a dark state are sequentially activated, located and deactivated. The localization accuracy of each molecule depends, of course, on the number of detected photons per molecule and can be as high as 2 nm. Over the whole field of view, these methods provide an average resolution in the order of several tens of nanometers.

8815-9, Session 2

Advances in STED microscopy: adaptive optics and total internal reflection microscopy *(Invited Paper)*

Travis J. Gould, Edward Allgeyer, Yale School of Medicine (United States); Daniel Burke, Martin Booth, Univ. of Oxford (United Kingdom); Joerg Bewersdorf, Yale School of Medicine (United States)

By breaking the classical diffraction limit, Stimulated Emission Depletion (STED) Microscopy has revolutionized far-field fluorescence microscopy. 25 nm resolution and better have been achieved in two dimensions imaging cultured cells.

We will present recent results on combining total internal reflection (TIR) with STED microscopy in our custom-built STED setup. The combination of TIR with STED limits excitation to a vicinity of about 100 nm to the cover slip and reduces bleaching and photo damage in live cell imaging.

STED microscopy has also recently been applied very successfully to imaging neurons even in the brain of living mice in two dimensions. The expansion to 3D super-resolution has also been demonstrated utilizing two opposing objectives or phase filters with a top-hat profile, its application to tissue has however been hampered by aberrations introduced by refractive index inhomogeneities.

Here we present our latest results in 3D STED microscopy of scattering specimens enabled by the integration of adaptive optics into a custom STED microscope. We will present our current research about the physical and technical concepts of adaptive optics STED microscopy as well as the latest biological applications of adaptive optics STED microscopy.

8815-10, Session 2

Far-field photostable optical nanoscopy (PHOTON) for super-resolution imaging of single protein-ligand binding complexes

X. Nancy Xu, Tao Huang, Lauren M. Browning, Old Dominion Univ. (United States)

We have developed a new-generation sub-diffraction imaging nanoscope, far-field photostable optical nanoscopy (PHOTON), for mapping individual ligand molecules and their binding sites in single protein-ligand complexes at nanometer resolution. Unlike fluorescence-based super-resolution imaging methods, PHOTON uses a standard far-field optical microscope equipped with a multi-spectral imaging system (MSIS) and a standard microscopic white-light illuminator (halogen lamp) as an illumination source. No laser excitation source is needed. Thus, conventional optical microscope is well suited for super-resolution imaging. Notably, PHOTON uses Rayleigh scattering of single noble metal nanoparticles as optical imaging probes, overcoming the drawbacks (auto-fluorescence, photo-bleaching, photo-blinking, phototoxicity) of fluorescence microscopy for imaging of proteins and living organisms. Intrinsic size- and shape- dependent localized-surface-plasmon-resonance (LSPR) spectra of single noble nanoparticles provide multiple-spectral (color) nanoprobes for sub-diffraction imaging, offering feasibility of probing of binding structures and functions of single protein-ligand complexes at nm resolution in real-time. PHOTON represents major breakthrough in sub-diffraction optical imaging with distinguished advantages, including superior photostability, superior spatial and temporal resolution, and no need of laser excitation sources and thereby effectively avoiding auto-fluorescence of proteins and phototoxicity to living organisms. Single nanoparticle optical biosensors serve as nanoprobes for both PHOTON and HRTEM, which enables us toward locate individual nanoparticles using both PHOTON and HRTEM and to validate nanometer spatial resolution of PHOTON. The work is supported in part by NSF (CBET 0507036) and NIH (R01 GM0764401; 3R01 GM076440-04S1).

8815-11, Session 2

High-resolution fluorescence imaging of a multi-layer cell cluster by saturated excitation (SAX) microscopy

Masahito Yamanaka, Kumiko Uegaki, Nicholas I. Smith, Satoshi Kawata, Katsumasa Fujita, Osaka Univ. (Japan)

To investigate cellular functions present in tissues, it becomes important to observe cell clusters in 3D culture, not merely cells on a hard glass or plastic substrate. However, specimens in 3D culture are typically thick and strongly scatter light, making high-resolution imaging difficult using conventional optical microscopy. Although recent developments in fluorescence microscopy have overcome the diffraction limit, super resolution imaging of thick samples still remains a challenge.

Here, we demonstrate the use of saturated excitation (SAX) microscopy for high-resolution fluorescence imaging of a multi-layer cell cluster. SAX microscopy improves the spatial resolution in three dimensions by detecting the nonlinear fluorescence emission induced by saturated excitation. Because the nonlinear fluorescence response is given predominantly in the laser focus, fluorescence signals from out-of-focus planes hardly contribute to the image formation, resulting to improvement of the depth resolution in a manner similar to two-photon excitation microscopy.

Using a SAX microscope and a typical confocal microscope, we observed HeLa cells cultured in a 3D matrix and stained by ATTO488-phalloidin. In the image obtained with SAX microscopy, the cross-sections of actin filaments are clearly separated at any observation depth, but not with confocal microscopy. From this experiment, we confirmed that SAX microscopy maintains the improved spatial resolution even in the observation of deeper parts of the sample.

Here, we also confirmed that SAX induces higher nonlinear fluorescence response in two-photon excitation, and demonstrated improvement of the spatial resolution in two-photon excitation microscopy.

8815-28, Session 2

Image resolution in optical nanoscopy *(Invited Paper)*

Bernd Rieger, Sjoerd Stallinga, Robert P. Nieuwenhuizen, Technische Univ. Delft (Netherlands)

Fourier Ring Correlation is proposed as a resolution measure for superresolution microscopy based on single emitter localization. The measure incorporates the effects of the emitter localization uncertainty and the density of localized emitters as well as the structure of the underlying object. It has been applied to simulated PALM and STORM images and experimental dSTORM data. In addition, an analytical expression has been derived for the resolution for two lines.

Common resolution concepts are either based on the localization uncertainty or on the Nyquist criterion for the average density of localized emitters. We propose a resolution measure that takes both localization uncertainty and density into account: the Fourier ring correlation (FRC). These concepts have long been used in electron tomography, but are new to the field of superresolution fluorescence microscopy. The definition of the FRC can be used to derive an explicit expression for the smallest distance between two parallel lines that can still be resolved. This expression provides new insights into the trade-off between the density of localized emitters and the localization uncertainty (following from the photon count per emitter), which we will discuss in great detail.

In order to correctly estimate resolution the number of on average localization of a single emitter are needed. To this end we present a method for estimating this count, without requiring prior knowledge about the spatial structure of the imaged structure. This presents one step closer to make localization microscopy a quantitative tool.

8815-12, Session 3

Cryogenic intra-molecular co-localization with Angstrom precision *(Invited Paper)*

Siegfried Weisenburger, Vahid Sandoghdar, Max Planck Institute for the Science of Light (Germany)

The advent of super-resolution microscopy during the past decade has advanced fluorescence microscopy beyond the diffraction limit [1]. One prominent technique - single molecule localization - is based on finding a fluorescent molecule's position by determining the center of its point-spread function with a much higher precision than the spot width. The localization precision is only dependent on the available signal-to-noise ratio, which is in turn mainly given by the number of photons that reach the detector [2]. Since the number of emitted photons of a dye molecule at ambient temperatures is limited by irreversible photobleaching, typical localization precisions are on the order of ten nanometers.

Here, we show that both the survival time and the number of emitted photons can be improved by more than two orders of magnitude at cryogenic temperatures. We use a high-NA cryogenic microscope and utilize the natural photoblinking and photobleaching of several dye molecules attached to a single biomolecule to demonstrate co-localization at Angstrom precision. We discuss the challenges, solutions and promise of this method for intra-molecular distance measurements with implications for super-resolution microscopy in general.

[1] S. W. Hell, Nature Methods 6, 24 (2009).

[2] R. E. Thompson, D. R. Larson, and W. W. Webb, Biophysical Journal 82, 2775 (2002).

8815-13, Session 3

Simpler 3D STORM in tissue *(Invited Paper)*

Ryan McGorty, Daichi Kamiyama, Bo Huang, Univ. of California, San Francisco (United States)

Obtaining super-resolution images tens of microns past the coverslip into tissue samples presents a number of challenges including depth-dependent aberrations, high background and the need for focus stabilization. In our investigations of Drosophila embryos we have dealt with these issues without using complicated systems such as two-photon excitation. We used a STORM compatible a high refractive index medium so that we could use high numerical aperture oil immersion objectives while avoiding the spherical aberration from the medium-coverglass refractive index mismatch. Due to the resulted absence of reflection at the sample-coverglass interface, we implemented a novel image-correlation-based method for active stage drift compensation. By correlating continually acquired bright-field images of the sample with reference images at multiple focal planes simultaneous to STORM data acquisition, we are able to stabilize the sample in all three dimensions. Finally, we are combining confocal techniques with STORM to reduce the amount of background when imaging deeper into tissue samples. Taken together, these modifications to STORM broaden the range of samples that can be investigated at the nanoscale level.

8815-14, Session 3

Targeting and tracking of individual proteins in live animals with nanometer accuracy *(Invited Paper)*

Fabien Pinaud, The Univ. of Southern California (United States); Hong Zhan, Christian Stigloher, Ecole Normale Supérieure (France); Ingo Gregor, Jörg Ederlein, Georg-August-Univ. Göttingen (Germany); Maxime Dahan, Jean-Louis Bessereau, Ecole Normale Supérieure (France)

It can be complicated to detect and image individual biomolecules in their native cellular environment. This task becomes even more challenging for living tissues. In animals, variable protein expression levels and inadequate intravital probe delivery can strongly complicate the specific detection of single biomolecules within the complex and generally highly auto-fluorescent environments of tissues. Recently we have developed a methodology named Complementation Activated Light Microscopy (CALM) that circumvents some of these limitations. In CALM, proteins of interest are fused to dark split-fluorescent proteins (split-FP) which are stochastically activated into bright FPs by irreversible complementation with exogenous synthetic peptides. We will describe how we use CALM to target and specifically image and track individual proteins with nanometer accuracy in cells and in living C. elegans nematodes. In C. elegans tissues, split-FP fusion protein can be used as stochastic single-pair FRET donors to a fluorophore attached to injected synthetic peptides, which allows for precise imaging of individual proteins with minimal interference from auto-fluorescence background, independently of protein expression levels and at micromolar probe concentrations.

8815-15, Session 3

Localization microscopy for the study of amyloid fibril formation

Dorothea Pinotsi, Gabriele Kaminski Schierle, Eric Rees, Clemens F. Kaminski, Univ. of Cambridge (United Kingdom)

Optical Localization Microscopy, a super-resolution technique, is a powerful tool for studying processes in biochemistry and cell biology due to its non-invasive and thus compatible with physiological environments nature. In this project we develop and apply a localization microscopy technique in order to study biological processes at the level of nanoscale. In particular, we use the direct stochastic optical reconstruction microscopy (dSTORM) with the main focus to study amyloid fibril self-assembly processes associated with protein aggregation in the context of neurodegenerative diseases, such as Alzheimer's and Parkinson's diseases. High resolution structural information on the fibrillar structures at each stage of the aggregation process is obtained through correlative atomic force microscopy (AFM) and dSTORM with molecule specific labeling. The dSTORM technique is ideally suited to determine the morphology of aggregates and of small intracellular structures with a 20 nm resolution, revealing details on a scale much smaller than the wavelength of the probing light. We are thus able to distinguish different oligomeric species and to relate the structure of the aggregates with their functional roles and effects in live cells. One of the main objectives is to study the interaction of protein aggregates with potential inhibitors in vitro and in cells. Furthermore, dSTORM offers us the ability to observe the dynamics of the aggregation process directly and non-intrusively; we follow the pathway of amyloid formation in real-time and in situ, with the ultimate goal to obtain a practical and reproducible model of protein aggregation for use in drug discovery.

8815-16, Session 4

Light manipulation for imaging application based on plasmonic nanostructures and metasurface *(Invited Paper)*

Wei Ting Chen, National Taiwan Univ. (Taiwan); Chia Min Chang, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan); Shulin Sun, National Taiwan Univ. (Taiwan); Kuang Yu Yang, Academia Sinica (Taiwan); Ming Lun Tseng, Yao-Wei Huang, Pin Chieh Wu, National Taiwan Univ. (Taiwan); Bo Han Cheng, Yen Ju Liu, Academia Sinica (Taiwan); Yueh-Hung Cheng, Chun Yen Liao, Hung-Kuei Tsai, Kuang Sheng Chung, Yu Lin Chen, Ding-Wei Huang, National Taiwan Univ. (Taiwan); Ai Qun Liu, Nanyang Technological Univ. (Singapore); Chih-Ming Wang, National Dong Hwa Univv. (Taiwan); Guang-Yu Guo, National Taiwan Univ. (Taiwan) and National Chengchi Univ. (Taiwan); Lei Zhou, Fudan Univ. (China); Din Ping Tsai, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan)

It is very important to manipulate surface plasmon polarization (SPP) waves both in the near- and far-field. Lately, three-dimensional focusing and diverging of SPP waves by a quarter circular structure composed of Au nanobumps have been studied. Such nanostructures show the promising light manipulation by way of providing additional wave vectors on SPP waves. By various plasmonic structures composed of arranged nanobumps, the scattering of SPP waves could be manipulated into specific light patterns in free space. By controlling the feature geometries of the plasmonic structures, we can modify the altitude, position, and focusing shape of scattered light as desired.

On the other hand, gradient-index meta-surfaces had been also found to exhibit extraordinary light-manipulation abilities, governed by a generalized Snell's law with an additional parallel wave vector provided by the radiation phase gradient of the meta-surface. Recently, we presented a new type of gradient meta-surface which can convert a propagating light into a surface wave with 100% efficiency. It provided that the phase gradient is large enough, and experimentally verified the idea in the microwave regime. Here, we designed and fabricated a gradient meta-surfaces working in visible region (~850nm) with broad-band functionality (750-900nm), and demonstrated by both experiments and numerical simulations that it can redirect an input light to a non-specular channel with high efficiency (~80%).

In summary, we provide two methods for light manipulation via designed plasmonic nanostructures. Our results lead to many practical applications, such as plasmonic micro-projector, plasmonic beam splitters, three-dimensional plasmonic circuitry, holography, etc.

8815-17, Session 4

Radiative and non-radiative properties of individual plasmonic nanostructures investigated by single particle spectroscopy *(Invited Paper)*

Stephan Link, Rice Univ. (United States)

A surface plasmon in a metal nanoparticle is the coherent oscillation of the conduction band electrons leading to both absorption and scattering. Ensemble extinction spectroscopy only measures the sum of both processes. However, single particle spectroscopy techniques allow one to separately determine the plasmon absorption and scattering. We have employed different polarization sensitive single particle spectroscopy techniques to investigate both radiative (scattering, luminescence) and non-radiative (absorption) properties of individual plasmonic nanostructures. In particular, we have used by dark-field scattering spectroscopy, photothermal heterodyne imaging, and confocal luminescence microscopy, which were all combined on one setup to study the same structures. Simulations aided in the interpretation of the results and allowed us to determine quantitative optical cross sections, which are difficult to obtain by ensemble measurements. To gain further insight about the relationship between structure and plasmon resonance, we correlated the optical response with the morphology of the nanostructure using electron microscopy.

8815-18, Session 4

3D dynamic imaging of intracellular molecules by surface enhanced Raman scattering

Kazuki Bando, Jun Ando, Osaka Univ. (Japan); Kai-Chih Huang, National Taiwan Univ. (Taiwan); Nicholas I. Smith, Katsumasa Fujita, Satoshi Kawata, Osaka Univ. (Japan)

Recent progress in Raman scattering microscopy has gained great interests from biologists and molecular scientists for label-free imaging of the molecular distribution of a sample. However, Raman scattering is an extremely weak photon process so that it requires a long exposure time for imaging, and the spatial resolution is limited to around half the wavelength of light. To overcome these limitations for live cell imaging, we use a gold nanoparticle captured in a living cell as a probe to analyze the biochemical composition along its path. The nanoparticle explores the living cell by detecting surface enhanced Raman scattering (SERS) signals, which contain local molecular information, resulting to the mapping of molecules along the cellular pathway with spatial resolution at nanometer scale. We introduced 80nm gold nanoparticles in a cell through endocytosis and observed the motion of a nanoparticle in three dimensions by using a dual-focus dark-field microscope. Raman scattering from the nanoparticle of interest was then obtained by a confocal Raman spectrophotometer with 676nm excitation laser. The laser focus position was controlled three dimensionally by a feedback system to trace the particle motion in real-time. As a result, we achieved a temporal resolution of 100ms for both particle tracking and Raman spectroscopy. Moreover, we observed a change in SERS spectra depending on the type of particle motion such as straight-forward motion and confined motion. Our results indicate that SERS spectra

from the nanoparticle could reveal information about the cellular function of biomolecules associated with organelle transportation and lysosomal accumulation.

8815-19, Session 4

Raman spectroscopy for intracellular localisation of meso-Tetraphenylporphyrin-gold nanoparticles conjugates

Rasoul Al-Majmaie, Nebras E. Al-Attar, Mohamed Al-Rubeai, James H. Rice, Dominic Zerulla, Univ. College Dublin (Ireland)

Biocompatible gold nanoparticles (GNPs) have gained significant interests in recent years for potential applications in nanomedicine due to their unique physical and chemical properties. Their use has become prominent in cancer research due to their inherently low toxicity and strongly enhanced optical properties associated with localized surface plasmon resonance (LSPR). GNPs have resonant light scattering properties and high absorption cross sections per unit volume that can enhance local fluorescence and plasmonic signals, making them invaluable tools in photothermal and photodynamic cancer therapy, diagnostic bioimaging and Raman spectroscopic detection.

The use of nanoparticles to deliver attached agents to a specific site is a promising tool to enhance efficacy, reduce toxicity, improved imaging, and tenability of the bio-distribution of a given therapeutic or imaging agent.

Raman spectroscopy is an analytical tool with many advantages over fluorescence spectroscopy in that it can provide a molecular fingerprint of a sample, which makes it attractive for material analysis and for biomedical applications. Surface enhanced Raman (SERs) can enhance the Raman signature enabling few and single molecules to be observed when the probe molecule is in close proximity to a plasmon active support such as a GNP.

In this study, we apply SERs as a non-destructive tool for intracellular localisation of porphyrin-GNP conjugates in cancer cells. We prepared conjugates of the hydrophobic photosensitizer meso-Tetraphenylporphyrin (TPP) and GNPs. The TPP-GNPs were characterized by by ultraviolet—visible absorption spectroscopy, fluorescence spectroscopy and transmission electron microscopy.

TPP-GNPs with a mean diameter of 12 nm were introduced into SW480 human colon adenocarcinoma cells. SERs was applied in conjunction with fluorescence microscopy to study the resulting materials. Our results show that the TPP-GNP nanomaterials are distributed inside the cell at particular locations. Overall our results indicate that Raman spectroscopy has the potential to be a high-throughput tool to localise nanoparticles in the subcellular environment.

8815-20, Session 5

Some improved techniques for better nanoimaging through tip-enhanced Raman scattering *(Invited Paper)*

Prabhat Verma, Osaka Univ. (Japan)

Due to the strong confinement of light near the apex of a metallic nanotip used in the tip-enhanced Raman scattering (TERS) measurements, microscopy based on TERS can achieve a high spatial resolution far beyond the diffraction limit of the probing light. Since light can interact with the intrinsic properties of a sample, TERS images provide information not only about the topographical distribution of the sample, but also the distribution of the intrinsic physical and chemical properties of a sample at nanoscale resolution. However, due to the physical restrictions, the ongoing research in TERS has arrived to a stage where further improvement looks difficult. Such high spatial resolution and enhancement of light field achieved in TERS is associated with the plasmonic effects at the metallic nanotip. Nevertheless, we have shown that by including some other effects in TERS, we can further improve the enhancement and spatial resolution. Some of these effects are based on Fano interactions, nonlinear phenomenon, chemical interactions and mechanical interactions. Here, we will show inclusion of such effects in TERS that can give much better results in enhancement and spatial resolution. Furthermore, by controlling the tip-sample separation with a precision of sub-nanometer scale, we can distinguish three different kinds of interactions between the tip and the sample, namely the plasmonic, the chemical and the mechanical interactions. This gives further strength to TERS in analyzing samples at extremely high spatial resolution.

8815-21, Session 5

High-resolution spectroscopic mapping of polymer fullerene blend films for organic solar-sell applications

Alfred J. Meixner, Dai Zhang, Xiao Wang, Eberhard Karls Univ. Tübingen (Germany)

Polymers and fullerenes are widely employed in the field of organic solar cells as the electronic donors and acceptors. The morphology and the photo-physical properties of the polymer and fullerenes blends at nanometer scale are critical for achieving a high performance of the solar cells. Employing a home-built parabolic mirror assisted apertureless near-field optical (Raman and photoluminescence) microscope, we demonstrated high resolution near-field spectroscopic mappings of the polymer:fullerene blend films. From the simultaneously recorded morphology and spectroscopic information, the interplay among the blend film morphology, the local donor and acceptor molecular distributions, and the photoluminescence quenching efficiency were discussed. The PL and Raman signals of the electron donor and acceptor have been probed at an optical resolution of approximately 10 nm which allow the direct identification of the chemical nature of the different domains. Moreover, we were able to reveal and quantify the local quenching, which is related to the electron transfer from donor to acceptor.

8815-22, Session 5

High-resolution tip-enhanced fluorescence imaging by controlling the tip-sample separation

Jun Yu, Satoshi Kawata, Prabhat Verma, Osaka Univ. (Japan)

While tip-enhanced Raman scattering (TERS) shows a continuous enhancement with the approach of a metallic nanotip towards the sample, the situation in tip-enhanced fluorescence (TEF) is different. A metallic nanotip not only enhances fluorescence, but it can also quench the fluorescence when it comes very close to the sample. As the tip approaches the sample in TEF, the resultant fluorescence signal is a result of these two competitive effects. Therefore, an efficient TEF microscopy can only be performed by maintaining an optimized tip-sample separation, where the resultant fluorescence signal is maximum. This requires a very precise control on the location of the tip, particularly in the direction perpendicular to the sample surface. Through our modified technique for controlling the tip-sample separation, we demonstrate high-contrast, high-resolution TFL imaging. This technique is also very useful in TERS, where by controlling the tip-sample separation, once can separate out three enhancements effects, namely the plasmonic enhancement, the chemical effect in enhancement and the mechanical effect in enhancement, because these three effects have different interaction lengths. Through our modified technique, we can control the location of the tip with a precision better than one nanometer and show how this leads to high spatial resolution nanoimaging.

8815-23, Session 5

A new technique for fabrication of better metallic nanotips for nanoimaging through tip-enhanced Raman spectroscopy

Takayuki Umakoshi, Osaka Univ. (Japan); Yaka-aki Yano, Tokyo Institute of Technology (Japan); Yuika Saito, Prabhat Verma, Osaka Univ. (Japan)

Tip-enhanced Raman spectroscopy (TERS) offers one of the best techniques for analysis and imaging of samples through Raman study at nanoscale spatial resolution. Important issue in TERS is to improve the detection sensitivity of inherently weak Raman scattering so as to observe varieties of samples. For enhancement of the Raman signal, fully metallized tips are utilized, which enhance signals through plasmon resonance at the apex. However, length of metal along the axis of the tip is on the order of a few to a few tens of micrometers, which means the plasmon resonant wavelength is much longer than the wavelength of the visible light used in TERS. From that point, if tips have metallic nanostructures on the apex, it gives better enhancement in the visible range compared with fully metallized tips.

In this research, we employed photoreduction as a facile fabrication method of metallic nanostructures at the tip apex. We found particular property of photoreduction that it occurs selectively at sharp corners, such as the tip apex of silicon cantilevers. Through this property, we succeeded in growing silver nanoparticles selectively at the tip apex. One of the advantages of the photoreduction is that the size of metal nanostructures is well controlled by optimizing various parameters. We controlled the size of silver nanoparticles from 100 nm to 400 nm by changing the laser exposure time. Furthermore, we obtained an order of magnitude higher enhancement of our fabricated tip compared with fully metalized tips by performing TERS measurements.

8815-24, Session 6

Multimodal and multispectral nano-imaging: accessing the structure underlying the function in polymers, proteins, biominerals

(Invited Paper)

Markus B. Raschke, Univ. of Colorado at Boulder (United States)

The properties of many functional soft-matter systems, including polymer heterostructures, organic photovoltaics, and biomembranes are typically defined on the mesoscopic few nm to sub-micron scale. Scattering scanning near-field optical microscopy (s-SNOM) has demonstrated its ability to access the relevant spatial regime. In combination with IR-vibrational spectroscopy s-SNOM provides molecular structural information. However, a yet higher degree of specificity, sensitivity, and selectivity with respect to specific molecular functional features is desired. I will discuss the strength of s-SNOM in a new combination with other nano-spectroscopic imaging modalities including nonlinear, ultrafast, and Raman, as well as other scanning probe modalities. In addition the multi-spectral combination of the strength of different coherent and incoherent IR sources including narrow band wavelength tunable continuous wave lasers, femtosecond OPO and OPA sources, broadband synchrotron radiation, and thermal near-field radiation provides an enhanced dynamic range to probe at the level of the microscopic intra- and intermolecular interaction. I will discuss several specific implementations from our recent work on block-copolymers, organic photovoltaics, proteins, self-assembled monolayers, and biominerals,

8815-25, Session 6

Super resolution mapping of the near optical field and the gradient optical force

Ryan M. Gelfand, Alireza Bonakdar, Omer G. Memis, Hooman Mohseni, Northwestern Univ. (United States)

We have developed a super resolution NSOM technique that can map both the near optical field and the optical force using an atomic force microscope. This technique could be very useful for characterizing MEMs/NEMs devices, plasmonic nano-antennas, nano-photonic devices and biologically active substrates. Unlike conventional NSOM techniques that rely on an aperture fabricated on the end of an AFM tip to collect the optical signal this apertureless technique uses a lock-in amplifier locked to the AFM tip vibrational frequency, to correlate the amplitude modulation of the back reflected optical signal to the strength of the optical field. And since we are not limited by the fabrication of an aperture the spatial resolution of the map is limited only by the size of a sharp AFM tip which for metallic coated tips can have a radius of curvature of 10 to 20 nm.

For optical force mapping the incident laser is modulated and the lock-in amplifier is used to correlate the amplitude modulation of the vibrating AFM tip to strength of the optical gradient force. And in this way one can get a very accurate mapping of both the optical force and the optical field for any substrate of interest as long as it can be back illuminated.

Lastly with an electrically monolithic substrate it is possible to correlate the amplitude modulation of the tunneling current to the optical field and obtain a spatial mapping that has a resolution of an STM, about 1 nm or maybe less.

8815-26, Session 6

Numerical modeling of apertureless scanning near-field optical microscopy

Arvindvivek Ravichandran, Edward C. Kinzel, Missouri Univ. of Science and Technology (United States); Robert L. Olmon, Univ. of Colorado at Boulder (United States); James C. Ginn III, Plasmonics, Inc. (United States); Jeffrey A. D'Archangel, The Univ. of North Carolina at Charlotte (United States); Brian A. Lail, Florida Institute of Technology (United States); Markus B. Raschke, Univ. of Colorado at Boulder (United States); Glenn D. Boreman, The Univ. of North Carolina at Charlotte (United States)

We present a HFSS model of a physically accurate SNOM probe (Arrow-NC) scanning over a patch antenna operating at 10.6 ?m. As in the real SNOM system, the probe/antenna are excited with an off-normal Gaussian beam. We calculate how the probe scatters light into the far-field (through a common lens with the illumination) for different positions of the antenna relative to the probe (both x-y scanning and separation of the height of the probe to capture tapping). The far-field signal is fitted as a function of the height of the probe relative to the surface. We use a Fourier analysis to construct the SNOM signal resulting from locking to different harmonics of the tapping frequency. This allows us to map the SNOM signal over the patch antenna. We compare this to the simulated near-field for the same antenna. This analysis shows that while the SNOM signal principally scales with the normal component of the field around the antenna there are some discrepancies in addition we see that for a small aperture detector, its position in the image plane effects the SNOM map of the antenna.

8815-27, Session 6

Transfer matrix for scattering-type near-field scanning optical microscopy

Nan Zhou, Yan A. Li, Xianfan Xu, Purdue Univ. (United States)

The scattering-type near-field scanning optical microscopy (s-NSOM) has been shown experimentally to be able to determine the amplitude and phase of near fields of nanostructures by polarization-resolved interferometric detection. However, it is challenging to compute the true near field from the measured signal because of the difficulties in simulating an actual s-NSOM measurement. In this work, we employ 3D numerical simulations to compute high harmonic signals in an s-NSOM measurement, scattered from various types of tips that are normally used in s-NSOM measurement. The strong interactions between tip and nanostructures to be measured, e.g., a bowtie nanoaperture, are considered. Demodulation of higher harmonic signals illustrates that with increasing harmonic order, the measured near field is in closer agreement with the anticipated results. Our results also show the limitations of spherical and small tip models commonly used in literature. More importantly, using the 3D calculations, we can establish a tip-dependent transfer matrix that relates the local near-field components with the s-NSOM signals, which characterizes the scattering of the tip with respect to different components. The transfer matrix greatly facilitates recovering the true local field from the measured s-NSOM signal through a simple backward transformation calculation.

8815-7, Session 7

Image scanning microscopy *(Invited Paper)*

Jörg Enderlein, Georg-August-Univ. Göttingen (Germany)

Classical fluorescence microscopy is limited in resolution by the wavelength of light (diffraction limit) restricting lateral resolution to ca. 200 nm, and axial resolution to ca. 500 nm (at typical excitation and emission wavelengths around 500 nm). However, recent years have seen a tremendous development in high- and super-resolution techniques of fluorescence microscopy, pushing spatial resolution to its diffraction-dictated limits and much beyond. One of these techniques is Structured Illumination Microscopy (SIM). In SIM, the sample is illuminated with a spatially modulated excitation intensity distribution, and the emerging fluorescence is imaged with a conventional wide-field imaging setup. By moving and rotating the excitation intensity distribution pattern in different positions and orientations, taking each time a wide-field image, a final fluorescence image is composed which has roughly double the resolution (laterally) of a conventional wide-field or a confocal laser scanning image alone. A similar technique is Image Scanning Microscopy (ISM). In ISM, the focus of a conventional laser-scanning confocal microscope (LCSM) is scanned over the sample, but instead of recording only the total fluorescence intensity for each scan position, as done in conventional operation of an LCSM, one records a small image of the illuminated region. The result is a four-dimensional stack of data: two dimensions refer to the lateral scan position, and two dimensions to the pixel position on the chip of the image-recording camera. This set of data can then be used to obtain a super-resolved image with doubled resolution, completely analogously to what is achieved with SIM. However, ISM is conceptually and technically much simpler, suffers less from sample imperfections like refractive index variations, and can easily be implemented into any existing LSCM. I will present the theoretical background of ISM and several of its applications in cell imaging.

8815-29, Session 7

Accurate 3D superresolution using phase retrieved pupil functions *(Invited Paper)*

Keith A. Lidke, Sheng Liu, Wesley D. Krueger, The Univ. of New Mexico (United States)

Single Molecule Localization based Superresolution requires the position determination of up to millions of fluorophores for each superresolution image. For speed and simplicity, fluorophore position estimation in three dimensions has often been implemented using simple Gaussian models, theoretical Point Spread Functions (PSFs) that do not account imaging system aberrations, or large, unwieldy, experimentally acquired 3D PSFs that can be prone to artifacts. Here we introduce a localization algorithm based on phase retrieved pupil functions and the maximum likelihood estimator. Pupil functions can contain information about specific aberrations present in the imaging system and can be used to calculate realistic 3D PSFs from a small set of Zernike polynomial coefficients that describe the pupil magnitude and phase [1]. This compact representation of the 3D PSF allows the PSF to be efficiently calculated as needed in an iterative update method implemented on GPU hardware in a similar fashion to our two dimensional localization algorithms [2,3]. We demonstrate the use of phase retrieved pupil functions for 3D localization by imaging several structures throughout whole cells using both dual focal plane and astigmatic imaging.

[1] B. Hanser et al, J. Microscopy 216, 32 (2004)

[2] C.S. Smith et al, Nature Methods 7, 373 (2010).

[3] F. Huang et al, Biomedical Optics Express 2, 1377 (2011)

8815-30, Session 7

Drift estimation for single marker switching based imaging schemes

Alexander Egner, Claudia Geisler, Laser-Lab. Göttingen e.V. (Germany); Thomas Hotz, Georg-August-Univ. Göttingen (Germany); Andreas Schönle, Stefan W. Hell, Max-Planck-Institut für Biophysikalische Chemie (Germany); Axel Munk, Georg-August-Univ. Göttingen (Germany)

In recent years, the diffraction barrier in fluorescence imaging has been broken and optical nanoscopes now routinely image with resolutions of down to 20 nm, an improvement of more than 10 fold. Because this allows imaging much smaller features and because all superresolution approaches trade off speed for spatial resolution, mechanical instabilities of the microscopes become a limiting factor. Here, we propose a fully data-driven statistical registration method for drift detection and drift correction for single marker switching (SMS) imaging schemes, including a guideline for parameter choice and quality checks of the drift analysis. The necessary assumptions about the drift are minimal, allowing a model-free approach, but more specific models can easily be integrated. We determine the resulting performance on standard SMS measurements and show that the drift determination can be routinely brought to the range of precision achievable by fiducial marker-tracking methods.

8815-31, Session 7

Approaching quantitative results in localization-based super-resolution microscopy: a robust and essential rejection algorithm and its applications in super fast live cell imaging

Fang Huang, Yu Lin, Tobias M. P. Hartwich, Joerg Bewersdorf, Yale Univ. (United States)

Single molecule localization techniques such as PALM/STORM/FPALM/dSTORM/GSDIM have been proven to be a promising technique which breaks the diffraction limit of light microscopy and provide images with resolutions as low as tens of nanometer in both fixed and living cells. Although these stunning super-resolved images provide helpful insights for biophysicist and microbiologists, quantitative analysis on the single molecule level such as protein number estimation and co-localization quantification has yet to be consider sophisticated. The main reason for the lack of quantitative analysis development resides in the additional

complexities that are introduced during analysis processes in this technique. In particular, the statistical behavior of rejection algorithms and localization estimate combination are not statistically addressed.

Here, we presents a specific tailored metric based on Log-likelihood Ratio (LLR) as an essential metric for rejection algorithms used in localization nanoscopy. We demonstrate its application as being one of the essential components which facilitate super-fast localization nanoscopy by strictly testing and obtaining the most accurate position estimates. By combining with our recent discoveries of a multi-emitter fitting algorithm and sCMOS technology, we demonstrate super-fast localization-based super-resolution microscopy on live cells by monitoring dynamics of protein clusters, vesicles and organelles at reconstruction speeds from 2 to 30 frames per second.

8815-32, Session 7

Mechanical and optical design and characterization of a 4Pi-FPALM super-resolution microscope

Edward Allgeyer, George Sirinakis, Fang Huang, Whitney Duim, Travis J. Gould, Joerg Bewersdorf, Yale School of Medicine (United States)

Light microscopy has long been established as a work horse in biology, with prolific applications spanning all areas of science. Unfortunately, the inability to resolve structures below the diffraction limit has greatly reduced the application of conventional light microscopy at length scales where many critical biological processes take place. As a result, innovations relying on marker switching have emerged that circumvent this fundamental limit and allow investigations at the sub-diffraction level [1]. Of these, localization based microscopy, in which sparse subsets of markers are stochastically activated, localized, and used to reconstruct images below the diffraction limit, has emerged as a popular modality.

Recently, combining a dual objective 4Pi geometry with stochastic switching localization based microscopy has realized sub-diffraction resolutions on the order of tens of nanometers in both the lateral and axial dimensions [2-3]. This improvement is achieved by taking advantage of the increased aperture angle and photon self-interference. Here we detail the mechanical design and function of a new auto-aligning 4Pi-FPALM system designed specifically with user functionality in mind. The instrument not only provides excellent 3-dimensional resolution improvements but additionally demonstrates outstanding optical and mechanical stability, reducing the need for user maintenance. In this presentation, we characterize the current localization precision, acquisition speed, and improvements of the microscope and present the first applications in biological systems.

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8815-33, Session 8

Advances in plasmonic sensing: new mechanisms for increasing chemical sensitivities *(Invited Paper)*

Naomi J. Halas, Rice Univ. (United States)

Recent developments in plasmonic nanoantenna design have extended the range of chemical sensors into the mid-infrared chemical fingerprinting region of the optical spectrum. These structures can be tuned to enhance the surface enhanced infrared absorption (SEIRA) signature of specific chemical functional groups. We have recently shown that individual antennas with a cross geometry manifest large SEIRA enhancements, eliminating the need for using large antenna arrays to obtain chemical signals. Antenna designs with narrow surface plasmon resonances and an electrical readout due to hot electron decay also have the potential to serve as chemical sensors: the geometry of these structures will also be discussed.

8815-34, Session 8

A new statistical approach for molecular identification by SERS

Thibault Brulé, Alexandre Bouhlier, Hélène Yockell-Lelièvre, Alain Dereux, Lab. Interdisciplinaire Carnot de Bourgogne (France); Renaud Seigneuric, Carmen Garrido, Univ. de Bourgogne (France); Eric Finot, Lab. Interdisciplinaire Carnot de Bourgogne (France)

SERS is a powerful measurement technique to obtain vibration modes of single biomolecules or more complex systems such as blood plasma. Existing SERS spectra result from a cumulative contribution of multiple proteins with different conformations and concentrations that are depending on SERS-active template utilized.

We propose a selective description of the serum by analyzing SERS contribution of individual proteins using a specific experimental approach [1] and multivariate analysis. The dynamics of rare events characterizing the Raman activity [2] of the serum on specially-synthesized nanoflowers was monitored. The observed large amplitude fluctuations of the spectra both in wavenumber and intensity require a careful and extensive multivariate data analysis. We will show that the use of the log-logistic distribution coupled with Principal Component Analysis (PCA) proved to be a robust and systematic technique to provide a unique spectral differentiation between the different serum proteins.

PCA is a specific linear transformation to convert the set of spectra having correlated variables into a set of linearly uncorrelated variables called principal components. This helps to gain valuable information about the degree of complexity of the results and reduces the dimension of observables to some principal spectra. PCA was so used to isolate the main spectra families [3].

The practical outcome of this study is the analysis of Heat Shock Protein 70 (HSP-70) in blood (SPEDOC European Project).

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8815-35, Session 8

Surface-enhanced infrared absorption using individual plasmonic antennas

Ke Zhao, Lisa V. Brown, Naomi J. Halas, Peter Nordlander, Rice Univ. (United States)

The development of antenna structures for surface-enhanced infrared absorption spectroscopy (SEIRA) is a topic of intense and growing interest for extending IR spectroscopy to zeptomolar quantities and ultimately to the single molecule level. Here we show that strong infrared spectroscopic enhancements can be obtained from individual gold nanoantennas using conventional infrared spectrometric sources.[1] The antenna structure dimensions can be tuned to enhance the IR modes of specific chemical moieties. Simulations of the electric field intensity in the antenna junction region reveal a maximum SEIRA enhancement factor of more than 12,000. These findings open new opportunities for analyzing infrared vibrations of exceptionally small quantities of molecules through widely accessible means.

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8815-36, Session 8

Blinking from surface-enhanced Raman scattering from individual single-walled carbon nanotubes: the effect of chemical modification of the nanotube

Nebras E. Al-Attar, Rasoul Al-Majmaie, Univ. College Dublin (Ireland); Ilona Kopf, Silvia Giordani, Trinity College Dublin (Ireland); James H. Rice, Univ. College Dublin (Ireland)

Single-walled carbon nanotubes (SWCNT) possess optical and electronic properties that can be potential tailored by the addition of a chemical group via covalent bonding to the nanotube thereby altering the conjugative network of the graphene sheet and creating changes in the electronic structure of the SWCNT. Surface-enhanced Raman (SERs) spectroscopy enables the imaging of single molecules.

SERs from single molecules possess random fluxing or blinking in the SERs intensity as a function of time. The study of such blinking processes has the potential to inform on the electronic structure of the molecule and how it interacts with its local environment.

SWCNTs with chemical groups covalently to the SWCNT surface were investigated using surface-enhanced Raman (SERs) spectroscopy at the single nanotubes level assessing the impact of such altering of the nanotube on the blinking process and in turn its interaction with the local environment.

We studied specifically SWCNTs and SWCNTs that have been chemically treated to improve their purity and also to alter the structure of the nanotube surface via covalently attaching carboxylic acid groups. Excitation of the nanotube samples at wavelengths in resonance with metallic and also semiconductor nanotubes was undertaken. Temporal fluctuations of SERs of purified and oxidised SWCNTs have been observed for both excitation wavelengths. These spectral features were assigned to arising from Raman scattering from single and few carbon nanotube molecules.

We studied both the spectral features and also the SERs blinking rates. The effect of chemical introduction of carboxylic acid moieties to the surface of the nanotubes was seen to tentatively reduce the temporal fluctuations in the SERs spectra. In addition both the power density and thickness of the silver substrate dependence on the Tangential modes G-band and disorder-induced feature D-Band have been studied for both highly purified and oxidised SWCNT.

8815-44, Session 8

Residual pesticide detection on food with particle-enhanced Raman scattering

Bikas Ranjan, Huang LiChuan, Kyoko Masui, Yuika Saito, Prabhat Verma, Osaka Univ. (Japan)

Modern agriculture relies highly on pesticides to protect agricultural food items from insects for high yield and better quality. Increasing use of pesticides has raised concern about its harmful effects on human health and hence it has become very important to detect even small amount of pesticide residues. Raman spectroscopy is a suitable nondestructive method for pesticide detection, however, it is not very effective for low concentration of pesticide molecules. Here, we report an approach based on plasmonic enhancement, namely, particle enhanced Raman spectroscopy, which is rapid, nondestructive and sensitive. In this technique, Raman signals are enhanced via the resonant excitation of localized plasmons in metallic nanoparticles. As plasmonic resonance frequency highly depends on the shape, size and material of nanostructures, hence it is possible to grow nanoparticles of a chosen shape and size to tune its plasmonic resonance with the resonance of Raman signals of any desired pesticide for better enhancement. Gold is a promising material that has ability to tune surface plasmon resonance frequency in visible to near-IR, which depends on shape and size of nanostructures. We synthesized desired shape and size of gold nanoparticles by using seed mediated growth method, and successfully detected very tiny amount of two pesticides, named benomyl and polycarbamate. We also confirmed that the detection of these pesticides was not possible by usual Raman spectroscopy.

8815-37, Session 9

Electron-tunneling assisted tip-enhanced Raman nanoimaging and nanospectroscopy *(Invited Paper)*

Alfred J. Meixner, Dai Zhang, Kai Braun, Eberhard Karls Univ. Tübingen (Germany)

We report about electron-tunneling assisted non-resonant Raman scattering spectroscopy and nanoimaging of molecules bound to a gold surface via a laser illuminated Au-tip Au-sample tunneling junction with a STM combined with a confocal microscope/spectrometer. For low bias voltages the TERS-spectra look similar to those recorded with shear-force tip-sample distance control. As the bias voltage increases we observe reversible mode specific enhancement and suppression of bands. Furthermore, reproducible differences in the Raman spectra are observed that are recorded at locations being only four nanometers apart from each other.

Efficient optical access to the tunneling junction is provided with a parabolic mirror for tip illumination and optical signal collection that are performed from above the sample under perfect diffraction and polarization conditions with a radially polarized laser beam. No restrictions apply with respect to the conductivity or transparency of the samples.

8815-38, Session 9

Raman spectral mapping of a single molecule with sub-nm resolution *(Invited Paper)*

Zhenchao Dong, Univ. of Science and Technology of China (China)

Visualizing individual molecules with chemical recognition is a longstanding target in catalysis, bio-science, and molecular nanotechnology. Molecular vibrations provide a valuable “fingerprint” for this identification. The spectroscopy based on tip-enhanced Raman scattering (TERS) has opened a path to obtain enhanced spectral signals thanks to the strong localized plasmonic field originated at the tip apex. The use of TERS has been pioneered by several groups in an effort to drive down the spatial resolution of molecules with chemical identification through vibrational fingerprints. However, the best spatial resolution of the TERS imaging reported to date is still limited to a few nm, obviously not adequate for resolving a single molecule chemically. Here we demonstrate unprecedented sub-molecular Raman spectral imaging with spatial resolution below 1 nm, resolving even the inner structure of a single molecule and its configuration on the surface. This is achieved by spectrally matching the resonance of the nanocavity plasmon to the downward molecular vibronic transitions, thanks to exquisite tuning capability provided by low-temperature ultrahigh-vacuum scanning tunneling microscopy. Our spectral-matching technique not only allows for chemical imaging at the single-molecule level, but also offers a new avenue to study optical processes and photochemistry of a single molecule.

8815-39, Session 9

Low-frequency Raman investigation and tip-enhanced Raman imaging of graphene

Kazumasa Uetsuki, Junto Tsurumi, Yuika Saito, Satoshi Kawata, Prabhat Verma, Osaka Univ. (Japan)

We have investigated a mechanically exfoliated graphene sample and imaged its number of layers through the G/2D intensity ratio in Raman microscopy. We investigated the interlayer interaction to understand the stacking for 2, 3, and 4 layer graphene samples by exploring the low-frequency E*(low) mode in Raman scattering. This low-frequency mode was successfully observed through our specifically modified experimental system for the observation of low-frequency Raman modes. While most part of sample showed AB stacking, a small area showed ambiguous behaviour due to random stacking of layers. We could conclude that this area consisted of 4 graphene layers, which were stacked either in the form of two pairs of closet-packed stacking, or in the form of 2 layers in closet-packed stacking plus two single layers. In addition, tip-enhanced Raman scattering (TERS) microscopy allowed us to image the sample at high spatial resolution, where we were able to analyze the interlayer interactions at nano-scale. We were also able to analyze the defects in our graphene sample at high spatial resolution, where we particularly investigate the defects at the edges of a graphene sample.

8815-40, Session 9

Polarization analysis in tip-enhanced near-field Raman imaging

Toshihiro Mino, Yuika Saito, Prabhat Verma, Osaka Univ. (Japan)

Tip-enhanced Raman spectroscopy (TERS) has revealed molecular vibrations in nano-scale beyond the diffraction limit. However, polarization of near-field light in TERS measurements is still ambiguous, because we have only little control on the near-field light due to the difficulty of precise shape regulation of the metalized tip apex. Here, we investigated the plasmon mode excited at the tip apex under dipole approximation, and performed polarization near-field imaging with TERS. Scattered light from the tip apex was measured by defocus technique, which revealed that the dipolar plasmon mode was excited in a certain direction when the tip apex was small enough compared to the wavelength of incident light. The xy- (perpendicular to the tip axis) and z- (parallel to the tip axis) polarization in near-field were determined from the analysis of the dipolar pattern. We successfully obtained polarization TERS images of carbon nanotubes using the tips evaluated by our method. The G-band in Raman scattering of our sample was strongly excited when the nanotubes were aligned in the dipolar direction, whereas radial breathing mode was observed only in the case where the dipole had enough polarization components in z-direction. The results agreed well with our expectation in both xy- and z-polarization directions. This method allows us to successfully utilize not only for polarization analysis but also for quantitative analysis in near-field Raman imaging.

8815-41, Session 10

Plasmonic Fano resonances: applications in surface enhanced spectroscopies *(Invited Paper)*

Peter Nordlander, Rice Univ. (United States)

Metallic nanostructures with their ability of confining and enhancing incident light offer unique possibilities for manipulating light at the nanoscale.[1] Plasmonic nanostructures can also exhibit coherence effects such as Fano resonances where the interference between superradiant and subradiant modes produces extinction features with characteristic narrow and asymmetric line shapes.[2] Due to their narrower spectral width compared to standard plasmon resonances, Fano resonances can provide very large field enhancements. Using symmetry breaking it is possible to tune the Fano interference into specific regimes: a weak coupling regime suitable for LSPR sensing; and a critical coupling regime providing large field enhancements suitable for plasmon enhanced spectroscopies. Finally I will discuss several recent applications where plasmonic Fano resonances have been used to enhance surface enhanced spectroscopies such as SERS[4] and four wave mixing.[5]

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8815-42, Session 10

Nanogap-enhanced Raman spectroscopy (NERS) controlled by DNA *(Invited Paper)*

Yung Doug Suh, Korea Research Institute of Chemical Technology (Korea, Republic of)

A series of research efforts have been devoted to generate more reliable SERS hot spots endowing single molecule sensitivity in the past decade. Based on an idea that controlling the gap at the junction of two noble metal nanoparticles and putting only a single molecule into this gap a priori is the key to systematically study single-molecule SERS phenomena, we have adopted DNA double helix tethered with a single Raman dye at the center position to bind two gold nanosphere cores with a known distance determined by DNA double helix ruler. Then we narrowed down this initial gap to sub-1-nanometer with standard silver staining method in solution.

This nanogap-enhanced Raman scattering (NERS) controlled by DNA with single molecule sensitivity seems to share the same gap-plasmon based physics with gap-mode STM/AFM-TERS, nanogap SERS sensor array including bowtie nano-antenna, and even conventional SERS, although only very rare portion of these nanogap sites can be formed in colloidal or thin film samples, resulting relatively low SERS enhancement factor compared with smSERS after ensemble average over a large area. In this presentation, I would like to review our own research effort to investigate this DNA-controlled NERS as well as the other kind of NERS phenomena.

8815-43, Session 10

Flocculation of metal nanoparticles towards efficient single molecule characterization in SERS *(Invited Paper)*

Masayuki Futamata, Saitama Univ. (Japan)

Single molecule detection by Raman scattering can be achieved using a coupled localized surface plasmon (LSP) of adjacent metal nanostructures, by controlling the nanogap size and the adsorption of target molecules. For this purpose, we have studied flocculates of silver and gold nanoparticles (AgNPs, and AuNPs), which are a few closely adjacent nanoparticles, providing various molecules with enormous SERS intensity in solutions1-2. First, the adsorption of cationic and neutral R6G molecules on Au nanoparticles was elucidated by surface enhanced Raman scattering on the basis of the flocculation method3. The steric hindrance at hydroethyl amino (-N(H)Et) groups in R6G was evidenced by the observation that R6G+ adsorb on as-prepared AuNPs only with electrostatic forces, in contrast to the electrostatic and chemical adsorption of R123+ with dihydro amino (-NH2) groups on as-prepared AuNPs. Large steric hindrance at the amino groups in R6G yielded saturated coverage of 700 molecules/AuNP for R6G+ significantly fewer than 1000 molecules/AuNP for R123+. In addition, neutral R6G0 on AuNPs showed markedly enhanced peaks at 1200-1600 cm-1, which were not observed in Raman spectra of R6G0 in bulk solution, and also in SERS of R6G+ on AuNPs. These bands are attributed to vibrational modes of an outer-phenyl ring and ethyl amino groups, which are vertical to a xanthene plane, on the basis of theoretical analysis of molecular vibrations. Thus Raman scattering of these bands are enhanced under an inclined orientation of R6G0 molecules chemisorbed on AuNPs via lone pair electrons at amino groups. Second, flocculates of AgNPs were formed using p-mercaptobenzoic acid (PMBA) to prove the relevance of this method for various species4. Electrostatic interaction between dissociated PMBA and counter ions, as well as van der Waals force between protonated PMBAs on AgNPs plays a crucial role in the flocculation. Dissociation of PMBA on AgNPs is determined not only by pH in solutions but also by surface coverage of PMBA. Mono- and divalent cations modified the ?COO- band at 1420 cm-1 by 20 cm-1 indicating distinct interaction of the cations with dissociated carboxylate anions of PMBA on AgNPs.

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8816-1, Session 1

High volume nanoscale roll-based imprinting using jet and flash imprint lithography *(Invited Paper)*

Douglas J. Resnick, Molecular Imprints, Inc. (United States)

The ability to pattern materials at the nanoscale can enable a variety of applications ranging from high density data storage, displays, photonic devices and CMOS integrated circuits to emerging applications in the biomedical and energy sectors. These applications require varying levels of pattern control, short and long range order, and have varying cost tolerances.

Extremely large area roll to roll (R2R) manufacturing on flexible substrates is ubiquitous for applications such as paper and plastic processing. It combines the benefits of high speed and inexpensive substrates to deliver a commodity product at low cost. The challenge is to extend this approach to the realm of nanopatterning and realize similar benefits. The cost of manufacturing is typically driven by speed (or throughput), tool complexity, cost of consumables (materials used, mold or master cost, etc.), substrate cost, and the downstream processing required (annealing, deposition, etching, etc.). In order to achieve low cost nanopatterning, it is imperative to move towards high speed imprinting, less complex tools, near zero waste of consumables and low cost substrates.

The Jet and Flash Imprint Lithography (J-FILTM) process uses drop dispensing of UV curable resists to assist high resolution patterning for subsequent dry etch pattern transfer. The technology is actively being used to develop solutions for memory markets including Flash memory and patterned media for hard disk drives.

In this paper, we have developed a roll based J-FIL process and applied it to technology demonstrator tool, the LithoFlex 100, to fabricate large area flexible bilayer wire grid polarizers (WGP) and high performance WGPs on rigid glass substrates. Extinction ratios of better than 10000 were obtained for the glass-based WGPs. Two simulation packages were also employed to understand the effects of pitch, aluminum thickness and pattern defectivity on the optical performance of the WGP devices. It was determined that the WGPs can be influenced by both clear and opaque defects in the gratings, however the defect densities are relaxed relative to the requirements of a high density semiconductor device.

Performance metrics of the LithoFlex 100, including throughput and pattern quality will be addressed. The application of this technology to the display market in addition to other markets will also be discussed.

8816-2, Session 1

Ultra-fast microfluidic and optofluidic prototyping based on controlled polymer dissolution

Andreas E. Vasdekis, Michael J. Wilkins, Jay W. Grate, Ryan T. Kelly, Sarah J. Fansler, Allan E. Konopka, Sotiris S. Xantheas, Pacific Northwest National Lab. (United States); Tsun-Mei Chang, Univ. of Wisconsin-Parkside (United States)

In this presentation, we discuss our recent results in developing a new polymer imprinting technique based on controlled polymer dissolution for microfluidic applications. The technique enables both the imprinting and bonding of thermoplastic polymers in very short time-scales; typically, complete assembly can be achieved in less than a minute. This represents a significant improvement over conventional thermal imprinting techniques, as well more recently developed injection techniques. We will present the details of the method and specifics of the involved underlying interfacial mechanisms as probed by chemical imaging methods and molecular simulations. Applications of the method in optofluidics as well as microfluidic cell-cultures will be discussed. Regarding the latter, as an example in microbiology, the growth of pure and mixed microbial populations was investigated in polystyrene micro-pore scale models; a double mean generation lifetime was revealed for the thermophile anaerobe Clostridium Thermocellum than under ideal culture conditions. Solvent based imprinting has been previously reported with enhanced performance in thin film applications and down to nm-scale resolution. The present work focuses on micro-scale features, with depths ranging from a few microns up to 100 µm.

8816-3, Session 1

Nano imprinted indium tin oxide sol-gel in light emitting diodes for effective elimination of total internal reflection

Sungjoo Kim, Chul Jong Ryu, Yang Hee Song, Gyeongmin Go, Jong-Lam Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

In the field of Group III-nitride light-emitting diodes (LEDs), much room remains for enhancement of light extraction efficiency because most of the generated photons from the active layer remain inside the LEDs because of the total internal reflection (TIR) at the semiconductor-air interface. To circumvent this problem, nano-imprint lithography has been offered for significant improvements of light extraction efficiency of the GaN LED device. However, reported imprinted materials such as SU-8 and PDMS are polymeric which have lower refractive index then that of top transparent electrode, indium-tin-oxide (ITO). Therefore, TIR and Fresnel reflection are occurred at the interface of ITO and soft resin, which limit the overall efficiency of the LEDs.

In this respect, we demonstrated the fabrication of novel hexagonal pyramid-shaped nanostructures with nano-imprinted index-matched ITO to eliminate TIR. Based on Monte-Carlo 3D ray tracing, we clearly confirm that light output intensity was increased with refractive index matching. Through refractive index matched nano structure, we enhanced the out-coupling efficiency of GaN based light emitting diodes (LEDs) about 12%. The 300C annealed ITO sol-gel has refractive index of 1.95, remaining the transparency (92%) and nano-structure. The nano-structured ITO sol-gel increases the diffused transmittance from 0.76% to 38%, leading to extract the wave-guided light from total internal reflection and fresnel reflection.

8816-4, Session 1

Engineering nano-particles for liquid bistable memory devices

Pascal André, Univ. of St. Andrews (United Kingdom) and RIKEN (Japan); Tsuyoshi Muto, M. Uchiyama, Tetsuya Aoyama, RIKEN (Japan); Jean-Charles Ribierre, RIKEN (Japan) and Ewha Womans Univ. (Korea, Republic of)

Hybrid materials based on inorganic nanocolloids (nCs) and organic semiconducting molecules have recently been the subject of intensive studies. This is due to potential advantages such as their relatively low cost and the opportunities to complement the properties of the organic materials by those of the inorganic constituents. Optoelectronics applications currently under investigation can been seen as having started with solar cells, but now include light-emitting diodes, and bistable memories. The latter class of device relies on hysteretic behavior of the conductivity when a voltage is swept between two electrodes. For each of them the mechanical flexibility is a key-concern for which emerging Liquid Electronics might have intrinsic advantages.[1-5]

Here, we report on and discuss the fabrication of optoelectronic devices based on a blend of inorganic nCs and 9-(2-ethylhexyl) carbazole (EHCz), coined as liquid carbazole. In contrast with other approaches which are based on solid thin films, these devices have a very simple structure with a single liquid layer sandwiched between two electrodes. Devices based on a liquid material and inorganic nanoparticles are an important step for the future development of organic liquid optoelectronic devices.[5]

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8816-5, Session 1

Nanofluidics integrated with plasmonics for ultra-high sensitivity devices *(Invited Paper)*

Irene Fernandez-Cuesta, Corrado Carbone, Enrica Montinaro, Scott D. Dhuey, Daniel J. Gargas, James P. Schuck, Stefano Cabrini, Lawrence Berkeley National Lab. (United States)

Plasmonic bowtie nanoantenna are able to confine and enhance the field intensity several orders of magnitude at a very small spot, that is the gap: this intense, nano-focused light is ultra-sensitive, what can be exploited for (bio)sensing. But there is a major challenge: placing the target element right at the antenna gap.

In this work, we have integrated a nanochannel running along a bowtie-shaped nanoantenna gap, what allows to deliver the analyte right into the sensitive area in a controlled fashion. The nanochannel dimensions are chosen to fit one particle or (bio)molecule, to be read one-by-one. The nanochannel is integrated in a complete fluidic system to facilitate the liquid control.

We have developed a wafer-scale fabrication process, based on nanoimprint lighotraphy (NIL), for the device fabrication. The all-transparent, multidimensional, multilevel polymeric device is made in one single step, by direct UV-NIL using the a stamp to imprint a hybrid polymer. The bowtie antenna are defined by shadow evaporation of chromium, a normal evaporation of gold, and lift-off.

Preliminary sensing results show the capabilities of the device. Single molecules of ?-DNA haven been stretched and driven trough the nanochannels by electrophoresis. The dark field resonant peak shifts 15 nm when the empty channel is filled with water. The antenna have been used also for “antenna-enhanced” Raman spectroscopy, and real time fluorescent single particle detection.

8816-6, Session 1

Impact of the Marangoni effect on the polymer thin film thickness profile after drying polymer solution coated on a flat substrate

Hiroyuki Kagami, Nagoya College (Japan)

We have proposed and modified a model of drying process of polymer solution coated on a flat substrate for flat polymer film fabrication supposing resist coating process in photolithography process. And we have clarified dependence of distribution of polymer molecules on the substrate on various parameters based on analysis of numerical simulations of the model. Above model consists of two elements. One is vaporization at the gas-liquid interface. The other is the diffusion inside the liquid film. The diffusion is divided into two kinds of diffusion, that is, diffusion of solvent with solutes due to gradient of the number density of particles per space and diffusion of concentration of solution. Because it is assumed that coated solution film on a flat substrate is very thin and therefore both Rayleigh number and Marangoni number are small enough, it is thought that Bénard convection or Marangoni convection does not occur and therefore it is sufficient to consider only above-mentioned two kinds of diffusion inside the liquid film. However there may be some sort of Marangoni effect regardless Marangoni convection does not occur. Therefore, in this study we add the Marangoni effect to the model. Concretely, we add Marangoni effect as pseudo-negative diffusion on an upper gas-liquid interface to the model. Then we evaluate effects of the Marangoni effect in the drying process through numerical simulation. And we see that solute on upper gas-liquid interface is attracted more strongly to the edge due to Marangoni effect.

8816-7, Session 1

Electrically tunable diffraction grating

Sun Il Kim, Jun-Hee Choi, Ho Young Ahn, Chan-Wook Baik, Jungkweuen An, Chilsung Choi, Kyungsuk P. Pyun, Samsung Advanced Institute of Technology (Korea, Republic of); Hong-Seok Lee, SAIT (Korea, Republic of)

We report on electrically tunable diffraction grating, where the refractive index of a Liquid Crystal (LC) was changed by applying DC bias to a metal nanograting (NG) structure. The structure consists of two parallel plates separated by a gap filled with LC molecules. The front and rear plates have structures of a rubbed polyimide (PI)/ITO electrode/fused silica glass substrate and a titanium NG electrode/n-type Si wafer, respectively. In the absence of DC bias of Vapp, the LC molecules are aligned parallel to the plate, in the rubbing direction of the PI. As Vapp increases from 0 V, the e-field near the metal grating strengthens sufficiently to rotate the LC molecules into the vertical direction following the e-field direction, while the orientation of the LC molecules in the space between the stripes remains unchanged. Up to the certain Vapp, the fraction of the vertically aligned LC volume increases to a maximum. With a further increase in Vapp above that value, the e-field even in the space between stripes is strong enough to drive the LC molecules to rotate into the vertical direction, hence reducing spatial modulation in the refractive index. At sufficiently high Vapp, all of the LC molecules are align nearly vertically and the spatial LC alignment contrast eventually disappears. Finally we obtained an active diffraction grating having a maximum refractive index difference (?n) of 0.088 and diffraction efficiency (?) variation of 0-16% with a large diffraction angle of 64° for incident light of 633 nm wavelength

8816-61, Session 1

Optical microscope combined with the nanopipette-based quartz tuning fork: atomic force microscope for nanolithography

Sangmin An, Seoul National Univ. (Korea, Republic of); Corey Stambaugh, National Institute of Science and Technology (United States); Soyoung Kwon, Kunyoung Lee, Bongsu Kim, Qwhan Kim, Wonho Jhe, Seoul National Univ. (Korea, Republic of)

We demonstrated the optical microscope (OM) combined with nanopipette-based quartz tuning fork - atomic force microscope (QTF-AFM) for nanolithography. The nanoparticle (Au, 5 nm), nanowire, PDMS solutions are ejected onto the substrate through the nano/microaperture of the pulled pipette, and the nano/microscale objects were in-situ formed on the surface with the proposed patterning system, while the position is defined by monitoring the phenomena on the substrate with a home-made OM. After forming of capillary condensation between apex of the pipette tip and the surface, the electric field is applied to extract out the inside liquid to the substrate and the nano/microscale objects are fabricated. The nanoscale patterning size can be controlled by the aperture diameters of the pulled pipette.

8816-8, Session 2

Vapor phase synthesis of XS2 atomic layers on SiO2/Si substrates

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Although single or few layer graphene has been shown to have many interesting properties as a supplement to silicon-based semiconductor technologies, its zero band gap limits its applications for optoelectronic and nanoelectronics technologies. Therefore, there have been considerable e?orts to open and tailor the band gap of graphene and shown that the band gap opening and tuning in graphene can be achieved by various methods such as doping and applying external electrical field. However, it is still far from satisfactory for practical applications. Very recently, atomic layered the transition metal dichalcogenides such as molybdenum disulfide (MoS2) and tungsten disulfide (WS2) with a direct band gap has attracted much scientific interest as an alternative to graphene due to its many potential applications. Here, we report the synthesis of XS2 (X: M, W) atomic layers on SiO2/Si substrates by a scalable chemical vapor deposition (CVD) technique based on the vapor phase reaction mechanism between MO3 (M: Mo, W) and sulfur. The effect of the various preparative parameters such as the sulfur concentration, pressure and deposition temperature on the structural, morphological, optical and electrical properties of XS2 atomic layers has been studied. The layers have been characterized by the scanning electron microscopy, optical microscopy, atomic force microscopy and Raman spectroscopy. The results have showed that sulfur concentration controls the grain morphology of XS2 layers, and MO3 determines the nucleation density. In conclusion, sulfur concentration, deposition temperate and MO3 morphology are very important process parameters in achieving atomic layers of XS2 with high quality and large scale. This synthetic approach is simple, scalable and applicable to other transition metal dichalcogenides such MoSe2 and WSe2.

8816-9, Session 2

Nanofabrication of integrated optical delay lines for RF and IR radiation pattern generation and steering

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We present advanced nanofabrication technologies used for the production of dynamic on-chip optical delay lines that generate and steer arbitrary radiation patterns using thermo-optic and electro-optic tuning. Photonic integrated circuits (PICs) designed for radio frequency (RF) and infrared (IR) radiation are described. RF PICs are combined with integrated detectors and RF antenna arrays, and used in applications ranging from phased array radar to communications, broadcasting and astronomy. IR PICs in the form of optical phased arrays with integrated grating-based optical nanoantennas enable solid state light detection and ranging (LiDAR), free space communications, and the selective excitation of modes in multimode fibers.

8816-10, Session 2

Artificially designed gold nanoparticles based on oblique-angle-deposition

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Well-defined homogeneous plasmonic nanoparticles are imperative to localize light and to use it for scientific interest and practical applications. In that sense, physical synthesis of nanoparticles by top-down routes, in which materials are vacuum deposited in a lithographically patterned polymer template, is a precise and reliable method to control material composition, particle size, and shape.[1-2] Here, we demonstrate that various shapes of the physically synthesized nanoparticles can be obtained by simple adjustment of incidence angle of deposited materials. Using nanoimprint lithography and oblique-angle-deposition, disk-, Petri-dish-, and ring-shaped gold nanoparticles are generated as well as their intermediate forms such as gold disks having a central bump or a central hole. Since it is possible to yield artificially designed gold nanoparticles with their unique light absorption/scattering properties, we expect the proposed method is quite useful to prepare various nanoprobes for bio-medical imaging and detection.

[1] J.-S. Wi, E. S. Barnard, R. J. Wilson, M. Zhang, M. Tang, M. L. Brongersma, and S. X. Wang, ACS Nano 5, 6449 (2011).

[2] J.-S. Wi, S. Sengupta, R. J. Wilson, M. Zhang, M. Tang, and S. X. Wang, Small 7, 3276 (2011).

8816-12, Session 2

Adjustable-density silicon nanoparticles prepared by femtosecond laser irradiation in alcohol

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Silicon micro/nanostructure (m/ns-Si) has attracted significant attention in recent years for both fundamental research and technical applications, such as self-cleaning, solar cell, photoluminescence generation, photodetectors and photodiodes. Several techniques (e.g., lithography and chemical etching) have been used to produce m/ns-Si with controllable size, shape and distribution. Compared with these methods, femtosecond laser (fs) micromachining is particularly attractive for its ease to simultaneously produce periodic micro/nanostructures and fabricate complex structures. However, they suffer from the disadvantages of complexity and high cost. In this paper, we present a new method to achieve adjustable-density silicon nanoparticles (NPs) by high energy femtosecondlaser irradiating on silicon under flowing alcohol circumstance.

Figure 1 shows the experimental setup. A Si (p-100) wafer is placed in a glass container filled with alcohol which is mounted on a three dimensional translation stage. The alcohol is continuously added in to insure the sample was always underneath the liquid-air interface of 200μm.

A series of large areas (300*300μm) of NPs are fabricated on silicon using this method at different scanning speed (V) with laser energy of 20μJ, as shown in Fig. 2. The line-by-line scanning method is employed. The interval of adjacent lines is 2μm. It can be clearly seen that the sizes of NPs achieved at different scanning speed are very uniform and almost all equals to 100nm. The density of NPs varies significantly with 4.1μm-2 (V=3000μm/s) to 13.4μm-2 (V=100μm/s).

8816-13, Session 2

The cause of irregular shape of the photonic crystal fabricated with recycled solvent

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Abstract

Managing the solvent waste has to be the most cost effective and environmentally acceptable method. Minimizing or reducing technique for the generation of waste solvent is essential investigation before planning feasibility of the large quantity preparation of the target product. To reduce the waste solvent, this investigation focused on the solvent ratio dependent diameter of the spheres and the effect on the photonic crystal by using the recycled solvent. The sphere diameter reduced, as the NH4OH concentration reduced without defect until 25 volume % of NH4OH. However, reducing further to 14 volume % of NH4OH produced different diameters of the spheres. To investigate the effect on the silica

sphere when the recycled solvent is used, the recycled solvent has been repeatedly used until 5 times. The diameter and shape of the silica spheres were same and without defect when the solvent used two times. However, the sphere shape became more and more irregular shape when the recycling time increased. The FTIR spectra of the spheres fabricated with various times recycled solvents are identical. To fine out the cause of the irregular shape, the solvent was evaporated after using the solvent 5 times and analyzed the residual. The FTIR result shows that the residual compound composed of Si-O-Si and Si-OH, which indicates that the irregular shape of the photonic crystal is caused by the residual compound. Therefore, the ideal concentration of NH_4OH is approximately 25 %, and the solvents can be used two times and then have to be distilled to remove the silica compound.

8816-14, Session 2

Solvent-dependent optical limiting response of platinum nanoparticles stabilized by [60] fullerene derivative

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The optical limiting performance of platinum nanoparticles protected by C60 derivative in chloroform, ethanol and dimethylformamide (DMF) was investigated experimentally with 532nm, 8ns duration laser pulses. It was found that the optical limiting ability is solvent-dependent. The solvent effect and origins of the optical limiting were analyzed. It was proposed that the absorption-induced scattering is the main mechanism causing the optical limiting behavior and solvent effect.

8816-15, Session 2

Effect of laser fluence and shot number on the diameter of hole in gold film

Yimeng Wang, Yachen Gao, Heilongjiang Univ. (China); Jifeng Zu, Shanghai Institute of Optics and Fine Mechanics (China)

In this paper, we demonstrated the fabrication of laser-induced holes in the 50nm gold film using 120fs laser pulses at 800nm wavelength in air environment. The surface morphologies-microstructures and diameters of holes were characterized using atomic force microscopy (AFM). It was found that, there are two kinds threshold of laser fluence for the formation of hole. And the diameters of holes were influenced by pulse energy and shot numbers. Based on the investigation above, the origin of hole was discussed.

8816-16, Session 2

Fabricating 3D spiraling metallic nanostructures with controlled chirality using metal-assisted chemical etching

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Fabricating nanostructures with complex, 3D geometry for applications such as chiral photonics can be extremely challenging using existing photolithography and etching processes. In this work we demonstrate a simple method to etch large arrays of chiral, 3D geometry in a single lithography/etch cycle using Metal-assisted Chemical Etching (MaCE) of silicon in conjunction with shaped catalysts. We also demonstrate that takes advantage of the catalyst remaining at the bottom of the template to electrolessly fill the templates from the bottom up using electroless deposition - enabling the facile fabrication of 3D metallic nanostructures with controlled, predefined chirality. The mechanism behind catalyst motion is detailed along with how catalyst shape controls etching mechanics and the resulting etching path.

Briefly, in MaCE a metal catalyst, such as Au, is patterned on a silicon wafer and then immersed in an etchant solution composed of Hydrofluoric Acid (HF) and an oxidizing agent, such as Hydrogen Peroxide (H_2O_2). The metal serves to create a traveling galvanic etching reaction by first catalytically reducing H_2O_2, consuming two electrons, and then injection two holes (h+) into the valance band of the silicon in contact with the metal. This creates a hole (h+) rich region of silicon surrounding the metal catalyst that is readily oxidized by the HF to form soluble H_2SiF_6. The etching reaction is perpetuated at the metal catalyst is driven into the substrate as the silicon around and beneath the catalyst is removed.

8816-27, Session 2

Surface-confined self-assembled Janus tectons: towards optical trapdoors *(Invited Paper)*

Antoine Colas, Ping Du, David Kreher, Fabrice Mathevet, Univ. Pierre et Marie Curie (France); Fabrice Charra, Commissariat à l'Énergie Atomique (France); André-Jean Attias, Univ. Pierre et Marie Curie (France)

One of the critical challenges in the field of two-dimensional (2D) supramolecular self-assemblies at surfaces is: how to exploit the room above the substrate, i.e. the third dimension perpendicular to the surface, to provide to the physisorbed adlayer potential functionalities in view of applications in nanoscience?

This is why developed a strategy aimed at the decoupling of conjugated molecules from a metallic surface, by lifting photoactive entities a few Å above the surface while maintaining the lateral organization of the array. We introduced the concept of Janus-like 3D molecular tectons [3,4], which are dual-functionalized building blocks exposing two opposite faces (A and B) linked by a rigid spacer : A is a pedestal designed for steering 2D self-assembly on the substrate (HOPG) and B a functional conjugated moiety.

Here we will present Janus tectons self-assembled as nanoporous networks and equipped with azobenzene derivatives. Due to the electronic decoupling we are able to observe the photoisomerization on a metallic substrate. By positioning the azobenzene over the cavities we can control the access.Then these janus tectons act as optical trapdoors

8816-18, Session 3

Chirped photonic crystals for spatial light filtering *(Invited Paper)*

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Spatial filtering plays an important role in optics as a tool for improving the spatial quality of the light beams. Usually a confocal system of lenses and diaphragm is used, which is however a bulky and sensitive to mechanical positioning system. Photonic crystals (PhCs) possess the angular bandgaps, which, properly engineered, can also provide the spatial filtering, as recently proposed. In particular, the larger angle spatial radiation components are reflected or deflected to diffraction maxima, and the lower angle components pass unaffected. Such PhC spatial filters could be an attractive alternative due to their tiny size and mechanical stability.

The first proof-of-principle experiments demonstrated the angular

filtering [L.Maigyte et al., Phys.Rev.A 82, 043819 (2010)], however the filtering efficiency was very small. The filtered-out angular areas were very narrow, of less than 1 degree. Here we extend the idea by using chirped PhCs, where the longitudinal period of the PhC linearly varies along the structure. Such linear chirp results in broadening of the angular bandgaps, and in much wider filtered angles. According to our calculations the performance of angular filters increase several times for proper chirp parameters.

We inscribed chirped PhCs into silicate glass using femtosecond direct laser writing technique and measured their filtering performance for 633 nm wavelength. Chirped PhCs exhibited up to 4 degrees wide filtering angle, which is around 10 times wider compared to the regular ones. In addition, we support the experimental data with theoretical calculations and show that PhC filtering performance could be improved even more.

8816-19, Session 3

Generation and collision of optical similaritons in dispersion-engineered silicon photonic nanowires

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We use a rigorous theoretical model that describes optical pulse dynamics in sub-micron silicon (Si) wire waveguides and comprehensive numerical simulations to demonstrate the formation of parabolic optical pulses in dispersion-engineered (tapered) Si waveguides. In particular, our theoretical model describes pulse reshaping due to the effects of free-carrier (FC) dispersion, FC absorption, second- and third-order dispersion (TOD), self-phase modulation, two-photon absorption, and frequency dispersion of the effective nonlinearity, as well as the influence of FCs on pulse dynamics. In the proposed scheme for the generation of parabolic pulses, a Gaussian pulse with width T0 = 200 fs and peak power P = 10 W is launched into an exponentially tapered Si waveguide whose width (w) and second-order dispersion coefficient (β2) vary between w = 820 nm and β2 = 4.63x10-2 ps2•m-1 at the input facet and w = 1030 nm and β2 = 0.575 ps2•m-1 at the output. The device operates in the mid-IR (2 µm). Our numerical simulations show that the adiabatically varying dispersion induces the generation of parabolic optical pulses, also called similaritons. The pulse reaches an optimally parabolic shape after a propagation distance of 7.5 mm, with the corresponding misfit parameter being I = 0.0025. Our simulations demonstrate that if the TOD and nonlinearity dispersion are negligible the misfit parameter becomes as small as I = 0.0019, illustrating the significance of higher-order linear and nonlinear effects. We anticipate that these ideas will find important applications in chip-scale nanophotonic devices for distortion-free pulse amplification.

8816-20, Session 3

Fast and high accuracy FDTD computations using numerical green functions based on a nonstandard finite difference model for photonics design

James B. Cole, Univ. of Tsukuba (Japan)

The finite difference time domain (FDTD) method is easy to implement and can compute scattering and propagation in arbitrary structures, but it has two major drawbacks: (i) accuracy is low unless a fine grid is used – which greatly increases the computational cost, and (ii) when the structure has features that are much smaller than a wavelength, many grid points are needed just to represent the structure. Problem (i) has been addressed with the nonstandard (NS) FDTD method. In this paper we address problem (ii) by introducing a discrete Green's function (DGF), which is evaluated using NS-FDTD. The DGF is not simply a numerical approximation to the Green's function of Maxwell's equations.Although a DGF can be costly to compute and requires more storage than FDTD, it need be computed only once and gives solutions for arbitrary incident fields – no further FDTD computations required. We have compared the accuracy of conventional FDTD, NS-FDTD and the NS-DGF calcuation and that the 3rd is superior to the 1st method, although the second is best of all. In computational photonics the DGF approach is advantageous for computing transmission and reflection spectra of subwavelength structures.

8816-21, Session 3

Optical mode modulation of AlGaInP multi quantum well laser diodes

Chih Tsang Hung, Sheng-Chieh Huang, Tien-Chang Lu, National Chiao Tung Univ. (Taiwan)

High efficiency AlGaInP-GaInP visible laser diodes (LDs) are critical components for applications such as laser display, distance measurement instrument, and photodynamic therapy for the therapy of cancer. In order to achieve high performance single mode operation, typical AlGaInP LD structure utilized GaAs regrowth or narrow ridge strip design for lateral carrier and optical confinement. However, these designs often lead to a low quantum efficiency or too high facet power density.

In this letter, high power AlGaInP-GaInP multi quantum wells (MQWs) LD adopted a high reflectivity passivation to modify the lateral optical mode distribution demonstrated low threshold current density and high conversion efficiency under a single mode operation. Compared to the conventional design of single-layer passivation, we deposited a multi-layer dielectric layer on the surface of semiconductor after completing lateral waveguide etching process. By adjusting the reflectivity of interface, we can change the near-field optical mode profile and it isn't workable to vary the far-field divergence beam but also to restrain the high order mode happening. Moreover, the corresponding threshold current was reduced obviously since the better lateral optical confinement results into a lower optical loss.

Under the same epi structure of AlGaInP visible LDs, we can reduce the horizontal far-field divergence angle from 16° to 10° by modifying the reflectivity of interface between passivation and AlGaInP epi layers from 1% to 80%. Besides, the diffraction spot of far-field pattern can also be improved obviously. Based on this design, its threshold current density can decrease from 14 A/cm2 to 10 A/cm2 at room temperature operation and LDs can be operated beyond 200mW without kink.

8816-22, Session 3

Magnetoresponse of a 15µm infrared quantum cascade detector

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Quantum cascade detectors (QCD) are a photovoltaic evolution of the quantum well infrared photodetector, designed to transfer electrons through consecutives cascades of levels when under illumination. QCDs have first been presented in the 8–12 µm band1-4 and now turn to very long wave infrared (12–20 µm), with potential astronomical and metrological applications.

We report the study of a GaAs/AlGaAs QCD heterostructure with a detection wavelength of 15 µm. The application of a magnetic field in the growth direction breaks the 2D in-plane continuum into discrete Landau levels allowing the interpretation of the different contributions of the scattering mechanisms.

Current measurements have been performed with and without illumination, magnetic field being applied parallel to the growth axis. A series of strong oscillations as a function of magnetic field is observed,

for both dark current and photocurrent. Based on a previously developed model, adapted and improved for 15µm QCD, these measurements allow us to identify the intricate scattering mechanisms responsible for the different transitions in the structure. The influence of temperature is also analyzed.

These experiments show that our model allow a better understanding of those complex structures. This model could also be used for the realization of the next generation of QCD.

8816-23, Session 3

Theoretical and experimental investigation of optimized evanescent-wave absorption sensors for extreme temperature applications

Michael P. Buric, Paul R. Ohodnicki, Benjamin Chorpening, National Energy Technology Lab. (United States)

Recently, there have been significant developments in evanescent wave absorption sensors for high temperature sensing applications based upon the optical responses of advanced thin film materials. We will demonstrate how such sensors can be utilized in a mode that allows for optimized sensing capabilities starting from basic theoretical considerations. We will also present experimental high temperature sensing results for fabricated sensors. Potential applications of the sensors to be discussed include a range of high temperature systems relevant for fossil energy and combustion monitoring such as industrial combustors or reaction vessels, solid oxide fuel cells, and gas turbines. In these applications, even a small increase in operating efficiency realized via careful observation of in-process parameters and implementation of real-time process controls can result in dramatic savings across the energy industry, illustrating the necessity of pursuing such techniques. It is hoped that sensors of the type described here will allow for unprecedented measurement-access to processes which present challenging high-temperature chemically reactive environments.

8816-24, Session 4

A highly stable and conductive ordered mesoporous carbon cathode for Li-S batteries

Dennis Pleskot, Wei Wang, Robert Ionescu, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

A novel ordered mesoporous carbon (OMC) material was developed as a highly conductive cathode for stable, long cycle-life Li-S batteries. The mesoporous carbon was developed using a triblock copolymer as a template, resol materials as the carbon source, and tetraethyl orthosilicate (TEOS) as the silicon source. The mesoporous carbon structure was obtained by heating and carbonizing a mixture of these ingredients. Afterwards, sulfur was impregnated into the carbon structure through a melt-diffusion process and the material was coated with an oxide layer to prevent diffusion of Li/S compounds. The resulting OMC material displayed a high pore volume with the size of individual pores on the order of nanometers. Several characterization procedures, such as SEM and TEM, were utilized to confirm the high level of porosity. Electrochemical half-cell and impedance measurements were performed on battery cathodes composed of this OMC material, with the results showing a high level of performance. Specific capacity was determined to be over 1200 mAhg-1 with good stability over 100 cycles. Impedance measurements also revealed a high conductivity for the cathode material. Thus, the OMC structure designed in this study improved upon the disadvantages of Li-S batteries, particularly the generally poor conductivity as well as cycle stability. This study therefore advances the use of Li-S batteries composed of OMC cathodes as an increasingly effective energy alternative to both contemporary Li-ion batteries and conventional fossil fuels.

8816-26, Session 4

Effects of quantum efficiency on PbSe/ PbSrSe multiple quantum well structures

Majed Khodr, American Univ. of Ras Al Khaimah (United Arab Emirates)

The effects of quantum efficiency on PbSe/Pb0.934Sr0.066 Se multiple Quantum well Structure were analyzed. We calculate and identify the critical design parameters required to optimize and study the MQW system as a function of five temperatures assuming the quantum efficiency is not equal to one and hence we include the effects of nonradiative recombination due to Auger recombination and carrier leakage over the barrier into the confinement layers. Inclusion of quantum efficiency in addition to temperature dependence increased the threshold current values by almost 10 times. Also, it was noticed that the threshold current density values dropped fast at small cavities and remained constant after some critical cavity length around 100 micro meter. When experimental quantum efficiency values were used, the threshold current values were higher than those found using the theoretical quantum efficiency values due to leakage current over the barrier.

8816-59, Session 4

Fabrication and characterization of nanostructured III-V thermoelectric materials

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Approximately two thirds of all fossil fuel used is lost as heat. Thermoelectric materials, which convert heat into electrical energy, provide a solution to recover some of this lost energy. To date, most commercial thermoelectric materials are too inefficient to be a viable option for most waste heat applications. This research proposes to investigate the fabrication and characterization of nanostructured III-V semiconductor thermoelectric materials to increase the performance of existing technology.

In order to improve thermoelectric material efficiency, either the lattice thermal conductivity must be lowered or the thermoelectric power factor must be increased. This research will focus on the latter by modifying the density of states of the semiconductor material and studying the effect of quantum confinement on the material's thermoelectric properties. Using focused ion beam milling, nanostructured cantilevers are fabricated from single crystal wafers. An all-around gate dielectric and electrode are deposited to create a depletion region along the outer core of the cantilever, thus creating an inner conductive core. The Seebeck coefficient can then be measured as a function of confinement by varying the gate voltage. This technique can be applied to various material systems to investigate the effects of confinement on their thermoelectric properties.

8816-17, Session 5

X-ray spectroscopies and linear combination analysis of electrospun polymer-carbon nanotube composites

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The technological importance of PDMS drives interest towards fiber production by electrospinning. This interest is augmented by the possibility to align multiwall carbon nanotubes (MWCNTs) in electrospun fibres, to produce either structurally sound or stimuli-responsive composites. The use of PMMA as carrier polymer is effective to electrospin PDSM; providing chain entanglement towards fibre production.

This work describes the near conduction band edge structure of electrospun MWCNT-PDMS-PMMA fibres by near edge X-Ray absorption fine structure (NEXAFS) spectroscopy. The polymers were blended in a 1:1 ratio and the resulting CNT composite fraction was 0.2 wt %. NEXAFS data was collected at the C K-edge in partial electron yield mode at normal, intermediate and glancing incidence.

NEXAFS spectra were acquired with the electric field both parallel and perpendicular to the fibres to comment on the orientation of the polymer chains as a result of electrospinning. Dichroic ratios calculated from the intensities of π^* and σ^* transitions confirm that though there is a preferential fibre alignment, the polymeric chains are not uniformly oriented.

Whereas no significant difference was observed between spectra from the composite and PDMS-PMMA acquired at normal and intermediate incidences, spectra acquired at glancing incidence differ dramatically. It is this incidence angle, therefore, that reveals information on the interaction between polymer and carbon nanotubes. A modified linear combination analysis method was employed in an attempt to model this interaction and identify the chemical groups involved.

8816-28, Session 5

Optical and electrical properties of green, olivine, and amber color nanopyramid light-emitting diodes

Kuok Pan Sou, National Chiao Tung Univ. (Taiwan); Yuh-Jen Cheng, Academia Sinica (Taiwan); Jet-Rung Chang, Shih-Pang Chang, National Chiao Tung Univ. (Taiwan); Mei-Chun Liu, Academia Sinica (Taiwan); Hao-Chung Kuo, Ken-Yuh Hsu, Chun-Yen Chang, National Chiao Tung Univ. (Taiwan)

We have demonstrated electrically driven green, olivine and amber color nanopyramid LEDs. The MQWs are grown on the semipolar facets of nanopyramids by using selective area growth technique on c-plane GaN. Spatially resolved cathodoluminescent analysis shows that the quantum well emission red shifts from the bottom to apex region of pyramid facets. The temperature dependent time-resolved photoluminescent measurement shows decent internal quantum efficiency despite the high In concentration. The radiative lifetime is much faster than (0001) plane MQWs, indicating significantly improved radiative recombination efficiency. From the radiative lifetime versus temperature measurement, the power law fitting curve shows that the lifetime increases linearly with temperature at near room temperature. This indicates that the emission is mainly from a 2D MQW system and there is no significant potential localization as would normally be observed for quantum wells grown on c-plane GaN substrate. It also shows the advantage of growing MQWs on semipolar nanopyramid facets, which have better quantum well uniformity and allow high In concentration. The electrical injection of these nanopyramid LEDs were demonstrated. The emission starts from the apex region of the pyramids as injection current increases. It is due the higher In content at the apex region and can be explained by the finite element method simulation and cathodoluminescent measurement. The emission is fairly uniform across the entire LED chip area despite the corrugated nanopyramid surface. The electrical injection demonstrates the promising potential of using nanopyramid design for high In content LED applications.

8816-29, Session 5

Realization of tellurium-based all dielectric optical metamaterials using a multi-cycle deposition-etch process

Sheng Liu, Jon F. Ihlefeld, Jason Dominguez, Edward F. Gonzales, John E. Bower, Bruce D. Burckel, Michael B. Sinclair, Igal Brener, Sandia National Labs. (United States)

We develop a multi-cycle deposition-etch process for fabricating Tellurium (Te) dielectric resonator metamaterials in infrared region. Te is a suitable resonator material due to its low loss at IR wavelengths and its large refractive index. First, we attempted to fabricate Te resonators by employing common metal lift-off techniques using e-beam lithography to define cubic voids in the e-beam resist, followed by Te deposition. However, pinch-off occurs when unwanted Te also deposits near the photoresist opening and accumulates to the point where the gap closes. Therefore, we develop this robust approach to circumvent this pinch-off problem by cycling deposition and etch processes. The key to the success is to first reduce the Te deposition thickness so that pinch-off doesn't close the resist opening and then perform a brief etch to clear the pinch-off. We successfully fabricated a series of samples in which the lateral edge dimension of the resonator was gradually increased while keeping the deposition thickness the same. All the samples show two transmission minima corresponding to the lowest (magnetic dipole) and second lowest (electric dipole) resonances. We also observe spectral overlap of magnetic and electric dipole resonances for different sizes' resonators.

This work was performed, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. #158883

8816-30, Session 5

Nano fabrication of high efficiency stacked crystal zone plate for x-ray optics

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The development of nanotechnology gives new possibilities for fabrication of high efficiency X-ray optical elements. The new type of stacked multilevel crystal Zone Plate (ZP) is fabricated by means of high resolution negative tone inorganic HSQ (Hydrogen Silsesquioxane or XR-1541) electron-beam resist. About 80% of the HSQ resist became SiO2 after electron beam lithography. This is a simple method to fabricate ZPs with SiO2 masks. Stacked multilevel silicon ZPs consisting of layers with bi-level zone profiles have been investigated. The composed multilevel ZP consists of two separate ZPs which have different structures. The distance between ZPs varied from 0mm up to 2mm. The efficiency of the phase ZP is 40.5%. The maximum efficiency for bi-level ZP without absorption is 68.4%. We obtain 54.6% efficiency for the stacked bi-level ZP when the distance between ZPs was 0mm. The radial distribution of intensity is determined as a convolution of the zone plate transmission function and the Kirchhoff propagator in par-axial approximation. The algorithm is based on the FFT procedure and studied by means of computer programming simulation.

8816-31, Session 6

Multi-stimuli-responsive elastomeric opal films: processing, optics, and applications
(Invited Paper)

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Synthetic opal layers and films, also referred to as photonic crystals, consist of monodisperse submicroscopic beads arranged in a face-centered cubic (fcc) lattice. They can be prepared by various techniques of deposition or spin coating from dispersions or in the melt under shear.[1] The latter technology, which takes advantage of core-shell beads consisting of a rigid core and a soft, elastomeric shell was developed in the last decade.[2,3] By this technique, large-area films can be produced, which reveal distinct iridescent colors caused by Bragg reflection from the fcc lattice as function of the viewing angle.[4,5] Based on their elastomeric properties, these films also show remarkable color changes due to a controlled lattice deformation.[6-8] Up to now, many potential applications of large-scaled elastomeric opals failed due to the presence of defects in the crystal lattice.[5] Recent developments lead to uniform samples on the multi-meter scale with monodomain bulk-ordering of the submicrometer components.[9,10] Progress in the field of tunable colloidal crystals embedded in films formed by the organization of highly monodisperse polymer-grafted beads with a responsive core-shell structure or by incorporating functional beads in a responsive polymer matrix revealed fascinating tunable materials and are promising candidates for e.g. sensing devices or as actuation systems.[11,12] By using external trigger such as the change of solvent, temperature, ionic strength, light, electrical field or mechanical stress, the lattice distance can be varied resulting in a tremendous change of optical properties.[13] Different bead architectures can be designed and many additives incorporated, for instance fluorescent dyes or inorganic nanoparticles increasing the film performance and hence expanding to even more potential applications. Here we present multi-stimuli-responsive, i.e., solvato-, pH-, iono- and mechano-responsive, elastomeric polymer opal films as promising candidates for a wide range of optical sensor applications. Highly functional elastomeric opal films combined with paper-based substrates show remarkable optical properties. Moreover, the porosity of the papers used permits the enhanced capacity of different analytes resulting in a very fast optical response due to a colloidal crystalline structure change. In combination with reproducible scale-up protocols for synthetic opals leading to industrial length scales, this approach can be used as a toolkit for tailoring a plethora of polymer-based soft sensors with a fascinating optical response. These highly functional materials have potential applications as next generation sensing devices and actuation systems, in particular when combined with inorganic nanoparticles, which are currently under investigation.

8816-32, Session 6

Silicon photonic crystal nanobeam electrooptic depletion modulator

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We theoretically investigate electrooptic modulation in silicon (Si) nanobeams produced by the depletion of electron and holes. As a silicon-on-insulator technology, the nanobeam is a single-mode Si strip channel waveguide or “photonic nanowire” that includes a resonant optical cavity at telecom wavelengths. The resonance is created by a 1D photonic crystal lattice which is a series of cylindrical air holes etched into the Si down to the buried oxide interface. In this way, a high transmission, high quality factor, waveguide-cavity system can be fabricated from a series of quadratically tapered holes on either side of a zero length cavity region.

Previous implementations of resonant nanowire electrooptic modulators consisted of a bus waveguide evanescently coupled through an air gap to a micro-ring , micro-disk, or micro-donut [1]. These designs result in a resonator that sits adjacent to the nanowire and results in a large footprint. In contrast, the resonator and optical waveguide we have devised are combined along a single nanowire. The smaller device area makes this advantageous both for fabrication considerations as well as lowering the required switching energy as compared to the micro-disk/micro-ring example.

Simulations have been performed for nanobeam structures with 8 hole pairs using a donor and acceptor concentration of 1018 cm-3 and 5 x 1017 cm-3, respectively. Initial results have shown 6 dB extinction with a 200 nm modulation length at a wavelength of 1530 nm.

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8816-33, Session 6

Nano plasmon device fabrications using dielectrophoretic(DEP) force

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Combination of nanowire and fluorescent nanoparticle which can be used as cavity-free, unidirectional plasmon guiding media and source, respectively, is an attractive material as nano-plasmonic devices. The trapping of 25nm diameter quantum dot(QD) was accomplished using the dielectrophoretic (DEP) force at nanowires which were self-grown and fabricated by e-beam lithography and lift-off. DEP force was induced around the nanowire using 3MHz sine wave. Finally, the QDs were manipulated to the nanowires and additional ‘QD on nanowire’ nanostructure was formed as a plasmonic device using DEP force.

8816-60, Session 6

Graphene/Elastomer composite based photothermal nanopositioners

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The addition of nanomaterials to polymers can result not only in significant material property improvements, but also assist in creating entirely new composite functionalities. By dispersing graphene nanoplatelets (GNPs) within a polydimethylsiloxane matrix, we show that efficient light absorption by GNPs and subsequent energy transduction to the polymeric chains can be used to controllably produce significant amounts of motion through entropic elasticity of the pre-strained composite. Using dual actuators, a two-axis sub-micron resolution stage was developed, and allowed for two-axis photo-thermal positioning (,100 mm per axis) with 120 nm resolution (feedback sensor limitation), and ,5 mm/s actuation speeds. A PID control loop automatically stabilizes the stage against thermal drift, as well as random thermal-induced position fluctuations (up to the bandwidth of the feedback and position sensor).

Maximum actuator efficiency values of 0.03% were measured, approximately 1000 times greater than recently reported for light-driven polymer systems.

8816-40, Session PWed

Nanoimprint lithography for soft and hard materials

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Recently, the creation, replication, and transfer technologies of nanostructures using a soft lithographic approach have received attention [1]. Many researchers and engineers have tried to materialize nanostructures, because nano-scale materials have some distinguishing characteristics from both micro- and macro-scale materials. The two main processes of engineering nanostructures are the top-down method, which is a direct engineering method for Si-type materials using photolithography or e-beam lithography, and the bottom-up method, using nano-imprinting. However, these methods are very dependent on the equipment used, and have a high process cost. They are also relatively inefficient methods in terms of processing time and energy. Therefore, some researchers have studied the replication of nano-scale patterns via the soft lithographic concept, which is more efficient and requires a lower processing cost .

In this study, accurate nanostructures with various aspect ratios are created on several types of materials. This work is highly applicable to the energy, optical, and nano-bio fields, for example. A silicon (Si) nano-mold is preserved using the method described, and target nanostructures are replicated reversibly and unlimitedly to or from various hard and soft materials. The optimum method of transferring nanostructures on polymeric materials to metallic materials using electroplating technology was also described. Optimal replication and demolding processes for nanostructures with high aspect ratios, which proved the most difficult, were suggested by controlling the surface energy between the functional materials. Relevant numerical studies and analysis were also performed. Our results showed that it was possible to realize accurate nanostructures with high depth aspect ratios of up to 1:18 on lines with widths from 100–200 nm. In addition, we were able to expand the applicability of the nanostructured mold by adopting various backing materials, including a rounded substrate. The application scope was extended further by transferring the nanostructures between different species of materials, including metallic materials as well as an identical species of material.

8816-42, Session PWed

Highly bright and durable light-generating composite films driven by mechanical stress and its prospective application to imaging devices

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Mechanically activated luminescence from solids (mechanoluminescence) is a classical optical phenomenon induced in a substance when stressed or cleaved.[1] Until now, many materials have been known to emit light by the application of stress even though scientists have not yet arrived at a clear understanding of the effect. However, no practical application has been realized because previous instances of mechanoluminescence have been weak and unrepeatable. Recently, we designed and demonstrated flexible composite films with highly bright and durable characteristics by focusing on the substance (polydimethylsiloxane; PDMS) that transfers the mechanical stress to the mechanoluminescent materials (copper-doped zinc sulfide, ZnS:Cu). By employing transparent PDMS with a high elastic modulus, we were able to realize in a simple manner a brightness of ~120 cd/m2 and durability over ~100,000 repeated motions.[2] Also, the simplicity of the fabrication process is also a strong advantage for various applications. Combined with these superior properties, in this presentation, we show the prospective application to imaging devices which uses a combination of color-tunable and patternable mechanoluminescent characteristics. We believe that the findings of this study can open a new window for developing new smart systems and opto-mechanical devices.

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8816-43, Session PWed

Signature geometry and quantum engineering

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Today's nano scale engineering allows us access to complex electromagnetic phenomena in the form of semiconductor chips. This paper is about how nano scale might also allow us access to the other fundamental phenomena including gravitational and the primary nuclear forces. Its not a paper full of equations and speculations but one introducing the reader to some special geometric structures, the origin of these structures and how they can be rendered to physical materials within an existing semiconductor industry. The central premise is that as we begin to manufacture forms at nano scale, geometry becomes the significant factor in defining function and this broadly corresponds with growing research in the subject of meta-materials. The recently discovered Transcendent Transcode Algorithm, a universal and absolute facet of prime numbers, provides a source of geometric design workable in many spatial dimensions and the ability to extract 2D and 3D sections from multi dimensional objects. Current string theory as used in particle physics leans more and more to considering multi dimensional concepts as constructs for basic physical phenomena. Quantum Engineering looks to resolve these two ideas into a single engineering objective: Signature Geometries – specific geometries existing on physical materials which are recognisable by fundamental physical forces. This recognition generates a reaction that can be considered a microscopic phenomena leading to the following definition for Quantum Engineering: "Take sections from an N dimensional signature geometry and render the forms to 2D or 3D nano scale materials. Select those forms that show microscopic recognition or coupling to the phenomena associated with the N space. Then create materials with billions of these rendered forms in a small space and generate macroscopic behaviour associated with the fundamental phenomena."

There are five sections to the book:

Section 1: Transcendent form and the Transcendent Transcode Algorithm(TTA).

Section 2: Signature Geometries and derivation from the TTA.

Section 3: Rendering Signature Geometries to current semi conductor production file standards.

Section 4: Quantum Engineering.

Section 5: The Philosophy.

Stefan Samociuk January 2013 www.transcoderesearch.com

8816-44, Session PWed

Three-dimensional crystal structures coating on optical fibers

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In this letter, the optical fiber with its smooth outer surface is selected as a substrate for the colloidal particles to self-assemble. The VD method is introduced to achieve this procedure of formation. The resulting colloidal crystals are characterized by scanning electron microscopy, which illustrate high order of the sample.

To deposit colloidal crystal films, the prepared fiber was then placed vertically in a vial with heated silica dispersion. The vial was immersed in an isothermal deposition chamber. The chamber was filled with water, placed on a rubber support. The whole experimental setup was placed into a constant-temperature, constant-humidity drying oven resting on a sturdy table.Typically, as the solvent evaporated, a uniform colloidal crystal film is formed on both the optical fiber outer surface and the vial walls.

A JEOL model JSM-5610 scanning electron microscope (SEM) operated at an accelerating voltage of 15kV was typically used for the observation of the particle arrangement in the colloidal crystal films.SEM images show that a long range ordering and highly ordered hexagonal array is produced. A continuous, uniform and highly-ordered hexagonal close-packed colloidal crystal structure with [111] crystallographic direction normal to the curved surface can be clearly observed, similar to the arrangement of the spheres on planar substrates.Square arrangement can be clearly observed, which we call the [100]-direction zones of the silica crystal films.We can also find that the dominant zones are the fcc structures with [111]- and [100]- direction zones, the regularly special coexistence pattern as well.

8816-45, Session PWed

Predefined planar structures in semiconductor surfaces patterned by NSOM lithography

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Semiconductor surface patterning is attractive and novel way how to improve properties of existing optoelectronic devices. So far, light emitting diode (LED) extraction efficiency improvement or radiation pattern modification is well described while using planar photonic structures in the surface of the device. In the meantime, there appear many applications requiring predefined structures with aperiodic or irregular design of patterned structures.

One of the promising optical technologies for planar structure fabrication is near field scanning optical microscope (NSOM) lithography. The method consists in employing the NSOM in illumination mode, where patterning of structures is done through a maskless exposure process performed by the optical near-field produced at the tip of a scanning fiber probe. Thereby, exposure of defined regions of the device on chip is performed so that different periodic and predefined arrangement can be achieved.

We demonstrate NSOM lithography as effective tool for semiconductor device surface patterning. The non-contact mode of NSOM lithography was used to pattern planar predefined structures in GaAs, AlGaAs and GaP surfaces in different two dimensional (2D) grids from 500 – 1500 nm. In this way, predefined metallic nanostructures on GaP surface were prepared which are used for organized GaP nanowire growth in solar cell applications. Predefined 2D arrangement of GaP nanowires was achieved and analyzed. Another application shows GaAs/AlGaAs-based LED with patterned structure in the emitting surface. Patterned air holes regions in the LED surface show the enhancement of radiation in comparison with the surrounding surface, what was confirmed from near- and far-field analysis.

8816-46, Session PWed

Patterned LEDs with planar surface structures

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Effect of planar structures on emission properties of light emitting diode (LED) surface is well known. Improvement of optical properties of LED such as directionality, far field profile or light extraction efficiency has been already demonstrated by implementation of planar photonic structures in LED surface. Although the effect of photonic as periodic structure on the light extraction efficiency is well documented, LEDs with predefined planar patterning have not been investigated so intensively. The predefined structure represents arbitrary planar pattern prepared in the LED surface; therefore not necessarily periodic.

From the diffraction on roughness-based effect it can be suggested, that implementation of predefined planar structure allows local enhancement of light emitting from the LED surface. Application of such structures can be attractive for local enhancement of light from defined areas of the LED surface. Also predefined structure with fresnel zone plate design is able to modify near- and far-field radiation characteristics.

We used optical techniques and focused ion beam for surface patterning of GaAs/AlGaAs based LEDs. Different predefined structures and the fresnel zone plate structures were patterned in the upper confinement AlGaAs layer. The fresnel zone plate structures were also prepared in thin polydimethylsiloxane (PDMS) layer using direct laser writing process. Patterned PDMS layer was directly applied on the surface of the LED structures. Surface of the LED structures was analyzed by employment of scanning electron microscope and atomic force microscope. The overall emission properties of prepared LEDs were investigated by near- and far-field analysis.

8816-48, Session PWed

Nanostencil lithography for fabrication of III-V nanostructures

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Nanostencil Lithography (NStL), while comparatively still in infant stages, is proving to be a viable option for low-cost and high resolution fabrication. An ideal stencil for NStL consists of a low-stressed silicon nitride membrane supported on a silicon chip with required patterned features in nanometer range that become apertures. The stencil is then used as a shadow mask and placed in close contact on top of a substrate/wafer. This pair is then ready for either depositing metal through the apertures in the stencil using variety of deposition techniques or etching the substrate using dry etching techniques with stencil acting as a mask. We fabricated 15 nm thick gold/chromium nanodots on III-V substrate having random distribution using a low-cost, nanoporous silicon grid (as nanostencil) having pores in the range of 10-60nm with 15% surface coverage. This grid was attached to GaAs substrate using a kapton tape in such a way that the membrane was touching the GaAs surface. Metal layers were deposited on this assembly using e-beam evaporator. We then fabricated well-ordered array of 700 nm diameter gold/chromium nanodots by fabricating nanostencil using focused ion beam on a TEM silicon nitride window/membrane. The gold nanodots (both random and ordered) can be used for vapor-liquid-solid nanowire growth (bottom-up), while the chromium nanodots can be used as a mask for reactive ion etching of III-V structures for fabricating nanowires (top-down approach). Fabrication of III-V nanowires and waveguides are ongoing using nanostencil lithography and results will be shown.

8816-50, Session PWed

Fabrication and characterization of graphene-palladium nanocomposite based hydrogen sensors

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For a future hydrogen-based economy, H2 sensors will be a critical for safety and will be widely needed in various applications. Among various sensing materials and noble metal catalysts for H2 sensors, a Pd nanostructure is a well-known and popular H2 detector. Recently, graphene has been shown to have excellent properties as a potential material to support a Pd nanoparticles (PdNP) catalyst or form Pd-graphene (Pd-Gr) nanocomposites, and has produced attractive results for H2 sensing in terms of high sensitivity and stability. Graphene oxide (GO) and reduced graphene oxide (RGO) have been widely used for various applications including photocatalysis, bio-technology, and sensing. GO is generated by oxidation of graphite and contains a wide range of functional oxygen groups such as hydroxyl and epoxy groups on the basal plane and carboxylic acid groups at the edges, which make GOs strongly hydrophilic. The hydrophilic properties created by attaching oxygen-functional groups of GOs yield a large number of advantages with respect to compatibility in MEMS/NEMS processes, biocompatibility, and producing functional graphene. In this work, we synthesized and investigated a Pd-Gr composite for resistivity H2 sensors and evaluated the influence of PdNP size in Pd-Gr composite on sensor performance. The sensors were fabricated in terms of large scale and batch process. The experimental reproducibility and working properties of sensors with respect to temperature and long period of time. Owing to good mechanical stability and high resistance to oxidation, the Pd-Gr composites exhibited good long-term stability in resistivity H2 sensors for at least six months

8816-51, Session PWed

Polydimethylsiloxane fibers for optical fiber sensor of displacement

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Polydimethylsiloxane (PDMS) is a silicone elastomer with properties which make it attractive for the optical application. PDMS is highly light-transparent material in wide frequency range, chemically inert, thermally stable, permeable to gases, isotropic and homogeneous, simple to handle and manipulate and has interesting rheological properties.

We demonstrate fabrication and optical properties of PDMS fiber integrated on the conventional optical fiber and its use for optical fiber displacement sensor. Silicone elastomer Sylgard 184 (Dow Corning) was used to prepare the PDMS fiber by drawing of partially cured silicone.

Depending on the PDMS fiber elongation, the signal change in intermodal interference was documented. Optical fiber displacement sensor using PDMS fiber is based on measurement of optical signal local minimum in visible spectral range generated by intermodal interference of circularly symmetric modes. Position of the local minimum in spectral range varies with fiber elongation; stretching the PDMS fiber by 230 micrometers corresponds to the wavelength shift from 688 nm to 477 nm. Therefore, using PDMS fiber, it is possible to determine the longitudinal displacement with accuracy of 1 micrometer.

8816-52, Session PWed

Optical properties of subwavelength patterned metal gratings for photonic device application and an alternative proposal

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We have investigated optical properties of subwavelength patterned metal gratings for photonic device application. It was known that optical transmittance of metal films with subwavelength periodic hole arrays can be controlled by applying a dielectric overlay to the film and the films can act as wavelength or frequency selective filters. Following advancement in lithography technology it could be applied up to complementary metal oxide semiconductor (CMOS) image sensors (CIS) by patterning metal layers placed on each pixel's photo detective device. However it is not easy to replace organic color filters applied on CIS up to date because the standard CIS structure has multi-metal layers, thick dielectric layers, and too thick metal layers for optical filters. In this work, we explore possibility to integrate the metal film into a CIS chip and present an alternative proposal by computer simulation utilizing finite-difference time-domain method. We applied aluminum (Al) for the metal film and the dispersion information associated with Al was derived from the Lorentz-Drude model. We expect that this work could contribute to search to apply subwavelength patterned metal gratings to photonic devices.

8816-53, Session PWed

Titanium dioxide fine structures by RF magnetron sputter method deposited on an electron-beam resist mask

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Titanium dioxide (TiO2) has been draw attention for wide range of applications from photonic crystals for visible light range by its catalytic characteristics to tera-hertz range by its high refractive index. We present an experimental study of fabrication of fine structures of TiO2 with a ZEP electron beam resist mask followed by Ti sputter deposition techniques. TiO2 thin layer of 150 nm thick is grown on ITO glass substrate with a fine patterned ZEP resist mask by a conventional RF magnetron sputter method with Ti target. The deposition was carried out with argon-oxygen gases at a pressure of 1.0 x 10 -2 Torr in a chamber. During the deposition, ratio of Ar-O2 gas was kept to 2:1 and the deposition ratio was around 0.5 A/s to ensure enough oxygen to form TiO2 and low temperature to avoid deformation of fine pattern of the ZPU resist mask. Design of the fine pattern are photonic crystal structure of periodic zigzag wires of 103 nm width, 608 nm in period[1]. TiO2 layers are white-transparent, amorphous, and those roughnesses are around 5 nm. We also studied transformation of TiO2 of the fine structures by baking at 500 degrees. XRD measurement for TiO2 shows that the amorphous form transforms to rutile and anatase forms by the baking while keeping the same profile of the fine structures. Our fabrication method can be one of a promising technique to optic devices on researches and industrial area.

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8816-54, Session PWed

Optical properties of aqueous dispersions of diamond nano-particles

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Metasurfaces demonstrate outstanding capabilities of modifying its optical parameters when changing its geometry at the nanoscale level. Our metasurface is an array of subwavelength apertures made in subwavelength thick metal layer. For this metasurface, we can shift transmission to shorter wavelenghts by depositing dielectric material of high permittivity into the cavities. Nanodiamonds, much smaller than the wavelength of light, can be suspended in an aqueous solution and guided into cavities by using electrophoresis. Metasurfaces are usually made from noble metals, therefore is convenient to use 2D optical array as an electrode to conduct electrophoresis of nanoparticles. The applied field controls the concentration of nanoparticles inside the apertures and on the top of the metasurface. Usually, fabrication of a metal metasurface with dielectric within apertures would require an irreversible process, e.g. sputtering, evaporation, or plasma-enhanced chemical vapor deposition. In contrast, the electrophoresis of nanoparticles is reversible by redispersing particles back in to suspensions and switching direction of the applied field. In our experiments, we deposited nanodiamonds with average diameter 3-4 nm into a 2D array of apertures with diameters of 350 nm and 200 nm made in 200 nm thick layer of gold. The accumulation of diamond nanoparticles was imaged by using scanning electron microscopy of the apertures. We also show that by increasing the concentration of nanodiamonds the effective refractive index of the aqueous suspension increases, as well as absorption and scattering. Results of material parameter characterizations at wavelength 512 nm are provided at different concentrations of nanodiamonds in suspensions.

8816-55, Session PWed

A tunable inverse-hemisphere-shaped Bragg grating sensor

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Stimuli-responsive diffraction gratings have been widely studied as chemical and biological sensors. The material which consists of the diffraction gratings changes its volume or periodicity in the presence of certain stimulus such as variation of pH, ion's concentration, etc. ,which leads to a shift in diffraction wavelength. Since the color change from the shift is readily perceptible with bare human eyes, this method is one of the most simple and convenient way to detect the environmental change.

In this work, we fabricated an inverse-hemisphere-shaped grating structure using soft lithography of close-packed nanospheres. The diffraction of two-dimentional sphere arrays are usually of great interest but that of an inverse-hemisphere-shaped grating have not much exploited so far. To compare the diffraction of these two structure, we measured the intensity diffracted into the Debye ring by using 633nm He-Ne laser and calculated the diffraction efficiency.

Then, we measured the diffraction wavelength shift induced from lattice change. The periodicity of the grating was tuned by two methods; mechanical strain and swelling in liquids. Diffraction was measured at a fixed angle utilizing a UV-VIS Spectrometer, a Tungsten Halogen lamp and a fiber optic reflection probe.

Also, Finite difference time domain (FDTD) simulation program (Lumerical) was used for better understanding of the diffraction phenomenon. We calculated the power scattered into a particular grating order of the grating structure, propagation direction, and strength of the grating orders at a certain wavelength.

8816-56, Session PWed

Piezoelectricity of ZnO nano-rods array prepared by hydrothermal method

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The piezoelectricity is most suitable for a various applications, such as electronic system, molecular sensors, biological electronics, diagnosis, and so on. Nano-generators have been a dramatic increase in the number of papers related to the formation of wire-like ZnO and Schottky barrier between ZnO nanowire and electrode. The ZnO nano-wires are well aligned but random tiered. In this study, we fabricated piezoelectric devices with ZnO nano-rods and thin film. The ZnO nano-rods were grown through nano-scale 2D patterns of oriented ZnO nano-crystals using a laser interference lithography followed by hydrothermal synthesis at 90 oC. ZnO nano-rods were preferred orientation with c-axis and wurtzite structure. We measured the electrical current from a ZnO nano-rods based on nano-generators. The AC-type current and voltage behaviors are attributed to the direct compression of ZnO nano-rods by an external force (under the load of 0.8kgf). The electricity of nano-rod piezoelectric device was 8.44x10-7Wh.

8816-57, Session PWed

A DLVO model for catalyst motion in metal-assisted chemical etching and methods to fabricate vertically aligned thin-film metallic nanostructures

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Metal-assisted Chemical Etching (MaCE) is a relatively new micro and nanofabrication technique in which a catalyst is used to create a traveling galvanic etching reaction that rapidly etches the silicon substrate with feature resolutions on the order of 1 -3 nm even over aspect ratios greater than 500:1. While the chemistry of MaCE has been reasonably well established for ~10 years, the mechanism behind catalyst motion was not. This research introduces a DLVO model for catalyst motion that was validated using plastic deformation of out-of-plane rotational structures and in-situ force-displacement measurements. The new information on catalyst motion allows us to better control the etching path of the catalyst during etching and readily fabrication 3D nanostructures in a single lithography/etch cycle. The vertically align thin film metallic nanostructures utilized in this work offer interesting opportunities for switchable metamaterials over the infrared and visible spectrums.

8816-58, Session PWed

Contamination control in ion beam sputter deposited films

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Ion beam sputter deposition is used in a wide variety of applications where precision film control and high quality, high performance layer materials are required. However, one of the difficulties of sputtering a target material with an ion beam is the control of the beam shape and collimation so as to avoid any energetic ions following trajectories whereby they could sputter other materials than the desired target material (e.g. from the surrounding furniture and fixtures); this results in a potential contamination of the depositing film with impurity material. The effect of this on the performance of the deposited film will depend on the particular application targeted, on the levels of impurities and on the nature of the impurities.

The conventional wisdom to guarantee high purity thin films in IBD has been to use a large vacuum chamber. The chamber size was important to minimise the effect of reflected high energy particles from the target surface sputtering chamber materials onto the substrate and to allow the use of large targets to avoid beam overspill onto chamber furniture: for example, chambers in excess of 1m3 have been used for the deposition of low loss dielectric mirrors. An improved understanding of beam trajectories and re-sputtered material paths has allowed the deposition of thin films with very low metallic impurity content in a chamber volume below 0.5 m3.

Thus, by optimizing the sputter ion source, target and substrate configuration, and by arranging suitable shielding made of an appropriate material in the process chamber, the levels of contaminants in the deposited films have been reduced to a minimum. With this optimum hardware arrangement, the ion beam process parameters were then optimized with respect to the ppm levels of contaminants measured in the films by SIMS analysis.

Using the deposition of SiO2 as a standard material for SIMS composition analysis and impurity level determination, it has been shown that our IBS deposition tool is capable of depositing films with contamination levels of <50ppm for the total of all metal impurities in the deposited films.

8816-34, Session 7

Theoretical characteristics of 1.55 µm InN based quantum dot laser

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Quantum dot (QD) laser has recently brought the breakthrough in optoelectronics and now it has been the most research effort subject matter around the world. Recently it is reported that InN has a band gap of around 0.7eV. This is compatible to 1.55 µm because the emission energy depends in a complex way on many parameters, both on the QDs (shape, dimensions, strain, and composition) and on the confinement layers (composition, residual strain) along with ground quantized energy levels of carriers. For long-wavelength 1.55 µm operations, InN based laser is predicted to be low cost, low power consumption, long-distance transmission, high-performance light sources for optical fiber communication. Recently the design and performances of 1.55 µm laser has been reported using InN based QD and QW technology. In this abstract, we present the theoretical characteristics of photon emission at 1.55-µm wavelength considering single layer InN quantum dot in the active region. The transparency threshold has been obtained at photon energy of 0.8016 eV and at zero normalized applied transition energy. The modal gain of about 12.5 cm-1 is obtained at the threshold current density of 51 Acm-2. External differential quantum efficiency of 65% has been achieved for the cavity length of 640 µm. The proposed structure with acceptable enhanced results will create a way to fabricate InN based quantum dot laser.

8816-35, Session 7

Metal super nano-grating and surface plasmon resonance spectrometer

Junpeng Guo, Hai-Sheng Leong, The Univ. of Alabama in Huntsville (United States)

A super nano-grating is a super-period nanostructure diffraction grating. The nanostructure within each super-period grating line supports localized optical resonance. For metallic nanostructures, the optical resonance is the localized plasmon resonance. In a super nano-grating, the super-period provides optical diffractions that follow the wavelength-period relation of the classical optical diffraction of thin gratings. Optical diffraction from a super nano-grating is an optical scattering process and also a radiation process, which directly carries the information of the local optical resonance. The optical resonance spectrum can be measured by using a linear photodetector array because the optical diffraction is angularly dispersive according to the wavelength.

Surface plasmon resonance modes in super period nanohole and nanoslit gratings are investigated through device fabrications and numerical simulations. A plasmon resonance mode splitting phenomenon has been observed in super-period nanohole gratings under the transverse magnetic (TM) polarization excitation. The phenomenon is explained as the result of the coupling between the localized nanostructure mode and the diffraction grating mode. Surface plasmon spectrometers are demonstrated using super-period nanohole and nanoslit gratings. A surface plasmon spectrometer is a spectrometer that can directly measure the surface plasmon resonance in metal nanostructures without using an external optical spectrometer. Surface plasmon resonance spectrometers open a new avenue for nanostructure surface enhanced spectroscopy.

8816-36, Session 7

Observation of sharp resonance peaks from a metal-embedded GaAs microcavity

Ryo Takemoto, Nagisa Ishihara, Nahid A. Jahan, Tomoya Asano, Xiangming Liu, Hideaki Nakajima, Hidekazu Kumano, Ikuo Suemune, Hokkaido Univ. (Japan)

Generation of quantum entangled photon pairs (QEPP) from a semiconductor quantum dot (QD) has been actively studied and demonstrated with biexciton (BX)-exciton (X) cascade emissions. However the two photons has different energies and are not indistinguishable. For advanced quantum information processing such as QEPP based quantum-key distribution (QKD) and swapping of quantum entanglement to realize quantum repeaters, solid-state photon sources for generating indistinguishable photon pairs are necessary. One of the possibilities is the simultaneous generation of QEPP with the use of a cavity effect. Conventional BX-X transitions is expected to be converted into the simultaneous generation of two identical photons. Photonic crystal (PC) nano-cavities exhibit high resonance Q, but there remains compromise to extract both photons efficiently to outer photon collection optics. We have developed a fabrication method to embed a GaAs-based semiconductor nanostructure in metal and recently observed the collection of ~20% of the photons emitted from an InAs QD inside a GaAs nano-pillar from the metal-embedded nanostructure surface. In this paper, we report the observation of sharp resonance photoluminescence (PL) peaks from the GaAs nano-pillars embedded in silver (Ag). The cavity resonance modes were monitored employing weak but broad luminescence of n-type GaAs that ranges from 800 to 1600 nm. The observed sharp resonance peaks showed the high resonance Q factor up to 4000. Observation of temperature insensitivity of these sharp peaks clearly shows the origin of these peaks as the pillar nano-cavity mode.

8816-37, Session 7

Nonlinear phenomena from a PIC attached gold tip using a plasmonic-whispering gallery mode hybrid system

Fang Ren, Hideaki Takashima, Hokkaido Univ. (Japan); Yoshito Tanaka, Hokkaido Univ. (Japan) and Hokkaido Univ. (Japan); Hideki Fujiwara, Keiji Sasaki, Hokkaido Univ. (Japan)

Localized surface plasmon fields induced in metal nanostructures have recently attracted considerable attention for the efficient light-matter interaction. However, it is still a challenge to focus incident light onto single molecule with 100% coupling efficiency because of the huge scale mismatch among photons, nanostructures, and molecules. In our previous research, we have proposed a new method using a tapered-fiber coupled microsphere in which we have succeeded in high coupling efficiency (~100%) by controlling the distance between a gold tip and microsphere, and have achieved second harmonic generation from the top of the gold tip using this plasmonic-whispering gallery mode (WGM) hybrid system. In this paper, nonlinear fluorescence was observed from Pseudoisocyanine(PIC)-terminated mercaptopropionic acid self-assembled monolayers formed on the surface of a gold tip via a tapered-fiber coupled microsphere resonator. The nonlinear fluorescence signal shows a quadratic dependence for the average incident power, which proves two-photon fluorescence from the PIC attached gold tip. Moreover, we also confirmed that the emission intensity from the PIC attached gold tip depends on the coupling efficiency between the PIC attached gold tip and microsphere exponentially. These results suggest the possibility that the efficient plasmon excitation via a tapered-fiber coupled microsphere resonator induces the strong light-matter interaction at the top of the gold tip and open up a possibility of inducing optical nonlinearities within a plasmonic-WGM hybrid system with high Q factor.

8816-38, Session 7

Generation and performance of localised surface plasmons utilising nano-scale structured multi-layered thin films deposited upon D-shaped optical fiber

Thomas D. Allsop, Aston Univ. (United Kingdom); Ron Neal, Plymouth Univ. (United Kingdom); Martin Dvorak, Aston Univ. (United Kingdom) and Brno Univ. of Technology (Czech Republic); Chengbo Mou, Aston Univ (United Kingdom); Kyriacos Kalli, Cyprus Univ. of Technology (Cyprus); Alex Rozhin, Aston Univ (United Kingdom); David J. Webb, Aston Univ. (United Kingdom)

A new generation of surface plasmonic optical fibre sensors is fabricated using multiple coatings deposited on a lapped section of a single mode fibre. Post deposition UV laser irradiation using a phase mask produces a nano-scaled surface relief grating structure, resembling nano-wires. The overall length of the individual corrugations is approximately 14 µm with an average full width half maximum of 100 nm. Evidence is presented to show that these surface structures result from material compaction created by the silicon dioxide and germanium layers in the multi-layered coating and the surface topology is capable of supporting localised surface plasmons. The coating compaction induces a strain gradient into the D-shaped optical fibre that generates an asymmetric refractive index profile which enhances the coupling of the light from the core of the fibre to plasmons on the surface of the coating. Experimental data are presented that show changes in spectral characteristics after UV processing and that the performance of the sensors increased from that of their pre-UV irradiation state. The enhanced performance is illustrated with regards to change in external refractive index and demonstrates high spectral sensitivities in gaseous and aqueous index regimes ranging up to 4000 nm/RIU for wavelength and 800 dB/RIU for intensity. The devices generate surface plasmons over a very large wavelength range, (visible to 2 µm) depending on the polarization state of the illuminating light.

8816-39, Session 7

Nano-imaging photolithography for plasmonic device applications

Alireza Bonakdar, Sung Jun Jang, Hooman Mohseni,
Northwestern Univ. (United States)

Low cost, large area and high throughput fabrication of sub-micron periodic optical nanoantennae is pivotal for commercializing surface plasmon enhanced devices such as solar cell, photodetector, metamaterial, molecular sensor, and optical communication. Here, we propose the nano-imaging photolithography method which can address these demands. Surface plasmon squeezes optical energy and shrinks the optical wavelength to deeply sub-diffraction limit resulting in resonance feature size on the scale of sub-micron in the visible and infrared region of light spectrum. Although, conventional photolithography in air is the well established, relatively low cost method to fabricate large area of optical elements with high throughput, sub-micron feature size of plasmonic antenna is not feasible as the imperfection physical contact between macroscopic mask and sample imposes sub-micron fuzzy features. As the alternatives, electron beam lithography and ion beam milling are fully capable to produce the state of the art devices with nanoscale feature sizes. However, they are relatively costly and time consuming specifically for large area applications.
The proposed nano-imaging photolithography method can transfer an arbitrary single macroscopic pattern to a micron/sub-micron feature scale. We are fabricating arrays of optical antenna such as nanorod and Bowtie antennas. Our homemade set up is low cost, very fast and is robust against the variation of UV source lamp and accurately adjustable for optimum operating point where the features as small as 100 to 200 nm are achievable. This method is based on our previous highly cited microsphere nanolithography which was limited to hexagonal closed packed array of nanoholes.

Conference 8817: Nanobiosystems: Processing, Characterization, and Applications VI

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8817-1, Session 1

Nanoengineered self-assembled two-dimensional and three-dimensional materials *(Keynote Presentation)*

Richard O. Claus, NanoSonic, Inc. (United States)

No Abstract Available

8817-2, Session 1

Self-assembled nanoparticle vesicles for optical and bio applications *(Invited Paper)*

Kuniharu Ijiro, Hokkaido Univ. (Japan)

A simple approach to the creation of colloidal assemblies from heterogenous nanoparticles is in high demand for the development of functional devices. The interparticle plasmonic coupling in the assemblies can produce collective properties different from those of dispersed particles, therefore metal and semiconductor nanoparticle assemblies are of considerable interest in many fields, such as material, analytical and medical sciences. Particularly, vesicular assembly of nanoparticles (nanoparticle vesicles) will propose new applications of nanoparticles facilitating the inner space, such as drug delivery, catalyst carrier, surface-enhanced Raman scattering (SERS) sensing platforms. Herein we demonstrated that surface modification with a semifluorinated ligand (SFL) efficiently produced sub-100 nm nanoparticle vesicles (-60 nm in diameter). We applied these nanoparticle vesicles for sensing system based on SERS, which gave largely increased Raman signals compared with general Raman signals. And photoinduced dr ug release from the nanoparticle vesicles was performed.

8817-3, Session 1

Hybrid gold nanocarriers with ultra-high chromophore loading for fluorescent imaging and photodynamic therapy *(Invited Paper)*

Patrice L. Baldeck, Univ. Joseph Fourier (France)

We will review our work on hybrid Gold nanoparticles (GNP) that are coated with polymers bearing photoactive molecules optimised for their fluorescence or PDT activity. Our first goal in using GNP is to load a large density of photoactive molecules onto a biocompatible nanoplatform. Our second goal is to optimize the molecule GNP interaction to improve the photoactive properties.

In this project GNP have typical dimensions in the 50-100 nm that are suitable for in vivo imaging and therapy. Their geometrical shapes included spheres, rods, bipyramids and stars. The spherical shape is efficient only when a spacer is used to maintain a minimum distance between the photoactive molecule and the metallic surface. However, more elongated shapes, or tipped shapes can be used for a direct grafting of photoactive molecules if their transition dipole moments are maintained perpendicular to the surface (J-aggregate type of interaction between the GNP and molecules). We will report on optical spectroscopy, fluorescence imaging, cell uptake, cytotoxity, and PDT action of several type of polymers coatings and photoactive dye loading.

8817-4, Session 1

Fabrication and characterization of OTFT memory based on DNA gate dielectric

Liang Lijuan, Kazuki Nakamura, Chiba Univ. (Japan); Sei Uemura, Toshihide Kamata, National Institute of Advanced Industrial Science and Technology (Japan); Norihisa Kobayashi, Chiba Univ. (Japan)

No Abstract Available

8817-5, Session 2

Biological and biologically inspired photonic materials and devices *(Keynote Presentation)*

Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States)

No Abstract Available

8817-6, Session 2

Grating formation in bi-layered DNA-complex devices: application to thin-film tunable dye lasers *(Invited Paper)*

Yutaka Kawabe, Toshifumi Chida, Toshinori Matsuoka, Kodai Fukuzawa, Kazuhiro Tada, Chitose Institute of Science and Technology (Japan)

Interaction of some organic dyes with DNA induces fluorescence enhancement through intercalation or groove binding, stimulating the development of compact tunable thin-film dye lasers. We have demonstrated amplified spontaneous emission, laser emission and its tuning via distributed feedback from a dynamic grating formed in DNA-surfactant complexes doped with cyanine or hemicyanine dyes.[1,2]

The formation of semi-persistent (or quasi-dynamic) grating is more preferable in order to realize stable and tunable laser oscillation, so we designed bi-layered laser devices composed of a DNA-CTMA layer doped with pyridine 1 and an PMMA layer including an azo dye, DR1. Under the excitation of the azo layer with interfering two beams for grating formation and the pumping of the emission layer with another beam, we observed laser emission from the device. The temporal behavior of the induced grating was controllable by varying the excitation energy and polarization allowing the optimization of grating properties suitable to applications. We achieved laser emission with semi-persistent grating and its switching by choosing an adequate energy of excitation.

Furthermore, monolithic DNA device having two functions as lasing and grating formation would be more promising. DNA-CTMA complex had been considered to be a poor matrix for grating inscription, but we found that doping of an azo-carbazole compound made it possible to inscribe gratings with high diffraction efficiency and moderately long lifetime which can be applicable to monolithic tunable laser devices.

[1] T. Chida and Y. Kawabe, Nonlinear Optics, Quantum Optics 45, (1-2), 85-91 (2013).

[2] Y. Kawabe, K. Sakai, Nonlinear Optics, Quantum Optics 42, (3-4), 273-282, (2011).

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8817-7, Session 2

DNA hybrid dielectric film devices for energy storage and bioelectronics applications *(Invited Paper)*

Donna M. Joyce, Air Force Research Lab. (United States); Fahima Ouchen, Air Force Research Lab. (United States) and Univ. of Dayton (United States); Narayanan Venkat, Air Force Research Lab. (United States) and Univ.of Dayton (United States); Steven R. Smith, Air Force Research Lab. (United States); Kristi M. Singh, Air Force Research Lab. (United States) and UES, Inc. (United States); Lei Zhu, Case Western Reserve Univ. (United States); James G. Grote, Air Force Research Lab. (United States)

No Abstract Available

8817-8, Session 3

Optofluidics and plasmonics for biosensing *(Keynote Presentation)*

Shaya Fainman, Univ. of California, San Diego (United States)

No Abstract Available

8817-9, Session 3

Lasing and random lasing in bio-polymeric dye doped systems *(Invited Paper)*

Jaroslaw Mysliwiec, Lech Sznitko, Adam Szukalski, Pawel Karpinski, Andrzej Miniewicz, Wroclaw Univ. of Technology (Poland)

The potential for photonic application of modified deoxyribonucleic acid with cationic surfactant cetyltrimethylammonium chloride, has been shown in many recent fields. Here we present results of detailed studies on lasing achieved in a double-layer system consisted of a biopolymer based matrix loaded with luminescent dye together with photochromic polymer and random lasing emission (RL). The laser action was achieved via distributed feedback configuration with third order of Bragg scattering on surface relief grating generated in photochromic polymer. The RL originates due to the scattering induced by the high surface roughness coming from the dye doped biopolymer. We show that lasing parameters for bio-polymeric system can be comparable with similar systems based on standard or pi-conjugated polymers and may contribute to commercialization of polymeric lasers.

8817-10, Session 3

Effect of UV-Crosslinking of DNA-CTMA biopolymer on its electrical and optical properties *(Invited Paper)*

Fahima Ouchen, Air Force Research Lab. (United States); Perry P. Yaney, Alyssa Lesko, Univ. of Dayton (United States); Emily M. Heckman, James G. Grote, Air Force Research Lab. (United States)

In this study, we investigate the effect of UV-crosslinking on the electrical and optical properties of DNA-CTMA biopolymer thin films. The crosslinking was achieved using Coumarin as a UV crosslinker.

8817-11, Session 4

Investigation of maple-deposited DNA films for graphene-based device applications *(Invited Paper)*

Adrienne Williams, Fahima Ouchen, Weijie Lu, John T. Grant, James G. Grote, Air Force Research Lab. (United States)

No Abstract Available

8817-12, Session 4

Grating inscription in DR1: DNA-CTMA thin film: simple models and experiment *(Invited Paper)*

Antoni C. Mitus, Grzegorz Pawlik, Wojciech Radosz, Jaroslaw Mysliwiec, Andrzej Miniewicz, Wroclaw Univ. of Technology (Poland); François Kajzar, Ileana Rau, Univ. Politehnica of Bucharest (Romania)

Recent experimental results indicate that the inscription of gratings in DR1:DNA-CTMA thin films displays some features of non-exponential grating amplitude growth with time [1]. We provide new experimental data and analyze them using a simple modeling based on semi-intercalation hypothesis [2] put forward for the interpretation of experimental data [3] and on computer-based analysis of local free volume in bond-fluctuating model of a polymeric matrix.

[1] G. Pawlik, W. Radosz, A.C. Mitus, J. Mysliwiec, A. Miniewicz, F. Kajzar, I. Rau, and J.G. Grote, Proc. SPIE Vol. 8464 (2012) 846404.

[2] G. Pawlik, A.C. Mitus, J. Mysliwiec, A. Miniewicz, and J.G. Grote, Chem. Phys. Lett., 484 (2010) 321.

[3] A. Miniewicz, A. Kochalska, J. Mysliwiec, A. Samoc, M. Samoc, and J.G. Grote, Appl. Phys. Lett. 91 (2007) 04118.

8817-13, Session 4

Spectral investigations on binding of DNA-CTMA complex with tetrameric copper phthalocyanines *(Invited Paper)*

Narayanan Venkat, Air Force Research Lab. (United States) and Univ. of Dayton Research Institute (United States); Joy E. Rogers-Haley, Air Force Research Lab. (United States); Rachel N. Swiger, Air Force Research Lab. (United States) and Southwestern Ohio Council for Higher Education (United States); Lei Zhu, Xiaoliang Wei, Case Western Reserve Univ. (United States); Fahima Ouchen, Air Force Research Lab. (United States) and Univ. of Dayton Research Institute (United States); James G. Grote, Air Force Research Lab. (United States)

No Abstract Available

8817-14, Session 4

Photoemission properties in Eu(III) complex doped DNA-CTMA film *(Invited Paper)*

Norihisa Kobayashi, Amika Sagara, Kazuki Nakamura, Chiba Univ. (Japan)

No Abstract Available

8817-15, Session 4

Deoxyribonucleic acid (DNA): a new nanomaterial for applications in electronics and in photonics *(Invited Paper)*

Ileana Rau, Univ. Politehnica of Bucharest (Romania)

Biopolymers in general, and the deoxyribonucleic acid (DNA) in particular, appear to be the choice materials for the next generation photonic and electronic devices. There are several arguments for the practical use of these materials, such as their origin from renewable resources, abundance, biodegradability, versatility and ease of processing. The DNA biopolymer can be extracted from the waste of food processing industry, thus can be cheap and is ecofriendly. Although the pure DNA represents a limited interest for practical applications (water solubility only, weak electron conjugation, low ionic conductivity) it can be functionalized with surfactants and with active molecules, providing desired optical and electrical properties. Some of these properties, like fluorescence, are enhanced due to the specific environment it offers. The DNA-surfactant complexes are insoluble in water and soluble in a number of organic solvents, offering large possibilities for functionalization. They form high optical quality thin films, which can be obtained by spin coating. In this talk the different doping mechanisms will be described and discussed. Different physico-chemical properties of obtained complexes, such as the photo-thermal stability, thin film processability, photoluminescence, linear and nonlinear optical properties will be reviewed and discusses. The observed nonlinear optical (NLO) molecules properties of thin films doped with some active molecules will be reviewed and discussed. Some practical applications of these materials will be also presented and discussed.

Acknowledgements

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8817-16, Session 5

Dielectric properties of BaTiO3 doped DNA at microwave frequencies *(Invited Paper)*

Guru Subramanyam, Eunsung Shin, Hailing Yue, Univ. of Dayton (United States); Fahima Ouchen, Roberto S. Aga, Carrie M. Bartsch, James G. Grote, Air Force Research Lab. (United States)

Nanoparticles of $BaTiO_3$ were introduced in to DNA for enhancing the dielectric properties of DNA films in this study. Different compositions of $BaTiO_3$ doped DNA thin films were studied using our patented capacitive test structure. Swept frequency scattering parameters were experimentally obtained for the devices in an inert atmosphere at room temperature. Our measurement results show increasing effective dielectric constant of the $BaTiO_3$ doped DNA as a function of the $BaTiO_3$ dopant concentration, with dielectric loss-tangent maintained relatively low. The presentation will discuss the processing of the films, the experimental results obtained, and the conclusions from this study.

8817-17, Session 5

Preliminary electrical and Raman characterization of DNA-CTMA films fabricated by drawndown bar

Perry P. Yaney, Univ. of Dayton (United States); Fahima Ouchen, James G. Grote, Air Force Research Lab. (United States)

A small, computer-controller drawdown bar device for coating glass-slide size substrates with thin films was designed and constructed. A variety of thin films of DNA-CTMA were fabricated. The results of electrical charcterization and micro-Raman spectroscopy studies are reported.

8817-18, Session 5

Improving energy transfer in QD-DNA photonic networks

Susan Buckhout-White, U.S. Naval Research Lab. (United States) and George Mason Univ. (United States); Christopher M. Spillmann, Mario G. Ancona, U.S. Naval Research Lab. (United States); W. Russ Algar, The Univ. of British Columbia (Canada); Michael Stewart, Kimihiro Susumu, Alan Huston, Ellen Goldman, Igor Medintz, U.S. Naval Research Lab. (United States)

There is considerable research in the area of manipulating light below the diffraction limit, with potential applications ranging from information processing to light-harvesting. In such work, a common problem is a lack of efficiency associated with non-radiative losses, e.g., ohmic loss in plasmonic structures. From this point of view, one attractive method for sub-wavelength light manipulation is to use fluorescence resonance energy transfer (FRET) between chromophores. Although most current work does not show high efficiency, biology suggests that this approach could achieve very high efficiency. In order to achieve this goal, the geometry and spacing of the chromophores must be optimized.

For this, DNA provides an easy means for the self-assembly of these complex structures. With well established ligation chemistries, it is possible to create facile hierarchical assemblies of quantum dots and organic dyes using DNA as the platform. These nanostructures range from simple linear wires to complex 3-dimensional structures all of which can be self-assembled around a central quantum dot (QD). The efficiency of the system can then be tuned by changing the spacing between chromophores, changing the DNA geometry such that the donor to acceptor ratio changes, or changing the number of DNA structures that are self-assembled around the central QD. By exploring these variables we have developed a flexible optical system for which the efficiency can be both controlled and optimized.

8817-19, Session 5

SHardonnay: the first fluorescent protein rationally designed for improved second-harmonic generation *(Invited Paper)*

Evelien De Meulenaere, Ngan Nguyen Bich, Katholieke Univ. Leuven (Belgium); Kristof Van Hecke, Univ. Gent (Belgium); Luc Van Meervelt, Jozef Vanderleyden, Koen Clays, Katholieke Univ. Leuven (Belgium)

Nonlinear imaging is steadily drawing more scientists' attention because of a number of advantages it has for application on live samples, and the additional molecular information that can be extracted from data based on second-harmonic generation (SHG) or coherent anti-Stokes Raman scattering (CARS). We set out to investigate the applicability of fluorescent proteins in simultaneous two-photon fluorescence and SHG imaging. For this purpose, we measured the second-order nonlinear optical properties of a small rainbow of fluorescent proteins, ranging from green to red, by means of hyper-Rayleigh scattering. A trend was observed showing an increasing first hyperpolarizability (β) for more red-shifted proteins. Only the yellow fluorescent protein, eYFP, exhibits a surprisingly low β. We hypothesized that this could be explained by centrosymmetric stacking of the chromophoric Tyr66 and the neighboring Tyr203 residues. We have removed the inversion center by mutating Tyr203 into Phe203, which resulted in a new yellow fluorescent protein with comparable linear optical properties, and an improved β. Based on the specific function (Second-Harmonic generation), the color of its emission, and in analogy with the "mFruit" names, we have named our mutant SHardonnay.

It is the first time that a fluorescent protein has been rationally altered for this purpose. SHardonnay exhibits an improved fluorescence quantum yield, and a 2-3 nm hypsochromic shift in its linear spectral properties. Structure determination by X-ray crystallography as well as linear optical characterization corroborate a correct folding and maturation. This study

can eventually lead to improved red fluorescent proteins for even better performance.

8817-20, Session 5

Investigation of DNA nucleo-bases thin films for potential application in electronics and photonics *(Keynote Presentation)*

James G. Grote, Air Force Research Lab. (United States)

No Abstract Available

8817-21, Session 6

Second harmonic generation from tyrosine containing peptides *(Invited Paper)*

Mehmet N. Nasir, E. Bergmann, Emmanuel Benichou, Isabelle Russier-Antoine, Noelle Lascoux, Christian Jonin, Françoise Besson, Pierre-François Brevet, Univ. Claude Bernard Lyon 1 (France)

The Second Harmonic Generation (SHG) response at the air-water interface from Tryptophan and Tyrosine-containing peptides at the air-liquid interface is presented. First, the quadratic hyperpolarizability of these aromatic amino acids is reported and compared to other amino acids, in particular the non aromatic ones. Then, the quadratic hyperpolarizability of short peptides is discussed with a particular emphasis on current models aiming at predicting this hyperpolarizability in terms of the hyperpolarizability of the amino acids themselves.

Based on these results, the properties of short peptides at the air-water interface are investigated. In particular, the light polarization analysis of the SHG response provides critical information on the kinetics of adsorption and re-arrangements at the interface. These results show that tryptophan and tyrosine can be used as endogenous molecular probes for peptides and proteins, paving the way for interface studies of biomolecules.

8817-22, Session 6

Bacteriorhodopsin-based bipolar photosensor for biomimetic sensing *(Invited Paper)*

Katsuyuki Kasai, Yoshihiro Haruyama, Toshiki Yamada, Makoto Akiba, Yukihiro Tominari, Takahiro Kaji, Toshifumi Terui, Ferdinand Peper, Shukichi Tanaka, Yoshitada Katagiri, Akira Otomo, National Institute of Information and Communications Technology (Japan); Hiroshi Kikuchi, NHK Science & Technical Research Labs. (Japan); Yoshiko Okada-Shudo, The Univ. of Electro-Communications (Japan)

Bacteriorhodopsin (bR) is a promising material for several applications. Biomimetic artificial retinas could be realized by using bR, since it is similar in its function to visual pigment rhodopsin. Optical excitation of bR at an electrode-electrolyte interface generates differential photocurrents while an incident light is turned on and off. The optical bipolar response offers the suitable sensing for vision applications such as motion detection and edge enhancement. This unique functional response is applicable to biomimetic sensing. We take notice of the functional vision system of an insect. It is known that the insect has realized the quick motion controlled by the optical flow sensing function, i.e., motion field detection. We are aiming to apply such insect-mimetic sensing based on the light-sensitive retinal protein bR to the autonomous mobile robot vision. The bipolar photosensor which consists of the bR dip-coated thin films patterned on two ITO plates and the electrolyte solution. This bipolar photocell will function as a biomimetic photoreceptor cell, i.e., the artificial visual receptive field. The bipolar structure has made the excitatory region and inhibitory region, since generation of the photocurrent is rectified in the cathodic direction. The experimental result of the edge detection, and the zero-cross character of the bipolar photosensor cell is similar to the feature of the ganglion cell receptive field. This result shows our bipolar cell acts as a basic unit of edge detection. We will also show the novel scheme for an insect-mimetic optical flow sensing function in the presentation.

8817-23, Session 6

Enhancing molecular logic and enzyme kinetics through modulation of temporal and spatial constraints of quantum dot-based systems that use fluorescent (förster) resonance energy transfer

Jonathan C. Claussen, U.S. Naval Research Lab. (United States)

Luminescent semiconductor nanocrystals or quantum dots (QDs) contain favorable photonic properties (e.g., resistance to photobleaching, size-tunable PL, and large effective Stokes shifts) that make them well-suited for fluorescence resonance energy transfer (FRET) based applications including monitoring proteolytic activity, elucidating the effects of nanoparticles-mediated drug delivery, and analyzing the spatial and temporal dynamics of cellular biochemical processes. Herein, we demonstrate how unique considerations of temporal and spatial constraints can be used in conjunction with QD-FRET systems to open up new avenues of scientific discovery in molecular logic circuitry and enzyme kinetics. For example, by conjugating both long lifetime luminescent terbium(III) complexes (Tb) and fluorescent dyes (A647) to a single QD, we can create multiple FRET lanes that change temporally as the QD acts as both an acceptor and donor at distinct time intervals. Such temporal FRET modulation creates multi-step FRET cascades that produce a wealth of unique photoluminescence (PL) spectra that are well-suited for the construction of molecular logic gates. We also demonstrate how QD-enzyme conjugate efficiencies can change with spatial constraints. In particular we analyze how enzyme density and QD size can regulate enzyme efficiency. These research advances in molecular logic and enzyme-QD efficiency open the door to future applications including multiplexed in vivo biodetection and biosensing for disease diagnostics and treatment.

8817-24, Session 6

SFG characterization of a cationic ONLO dye in biological thin films

Lewis E. Johnson, Pomona College (United States); Michael T. Casford, Paul B. Davies, Univ. of Cambridge (United Kingdom); Malkiat S. Johal, Pomona College (United States)

Biopolymer-based thin films, such as those composed of CTMA-DNA, can be used as a host material for NLO-active dyes for applications such as electro-optic (EO) switching and second harmonic generation. Previous work by Heckman et al. (Proc. SPIE 6401, 640108-2) has demonstrated functioning DNA-based EO modulators. Improved performance requires optimization of both the first hyperpolarizabilities (β) and degree of acentric ordering exhibited by the chromophores. The cationic dye DANPY-1 (Proc. SPIE 8464, 846409-D) has a high affinity for DNA and a substantial hyperpolarizability; however, its macroscopic ordering has not been previously characterized. We have characterized the acentric ordering of the dye using sum-frequency generation (SFG) spectroscopy and microscopy in surface-immobilized DNA and other biologically relevant thin films.

8817-25, Session 6

Integration of biological photonic crystals in dye-sensitized solar cells for enhanced photocurrent generation

Jeremy Campbell, Oregon State Univ. (United States)

Dye-sensitized solar cells (DSSCs) have been investigated as a low-cost alternative to silicon-based photovoltaics. Relying on a network of titanium dioxide nanoparticles for electron transport, these devices must balance photon capture with carrier collection. Adding photonic structures may increase light capture within these devices without undermining electron transport.

The recognition of photonic structures in nature has renewed interest in a class of single-celled photosynthetic algae called diatoms, which are abundant in all aquatic ecosystems. Diatoms biologically fabricate silicon dioxide cell walls (frustules) that contain intricate sub-micron pore arrays with length scales comparable to the wavelengths of visible light. We hypothesize that diatom biosilica may function as photonic crystal slabs to enhance light capture within DSSCs without increasing device thickness.

We have identified a broad optical resonance (>100nm) within the visible spectrum of diatom biosilica films in air. Additionally, a fabrication approach has been developed that allows for controlled and uniform placement of biosilica within DSSCs. Two strategies were investigated for diatom biosilica integration: as a discrete optical layer and as a distributed optical material within the bulk titanium dioxide. Characterization of the optical effects of biosilica integration throughout device assembly reveals a significant reduction in photoanode transmittance with biosilica addition (20-30%). The optical effect is lost when the liquid electrolyte is added due to the similar refractive indexes of the electrolyte and the biosilica. Functionalization of the diatom biosilica with titanium dioxide preserves refractive index contrast and restores the optical effects, resulting in photocurrent enhancements of 10-20%.

8817-26, Session PWed

Protein ‘smart’ micro/nano-biooptics via femtosecond laser direct writing

Yun-Lu Sun, Wen-Fei Dong, Hong-Bo Sun, Jilin Univ. (China)

Here, the proof-of-concept protein (Bovine Serum Albumin) microlenses were fabricated by femtosecond laser direct writing (FsLDW) system mainly composed of a nano-precision piezo stage and a two-galvano-mirror set respectively for the horizontal and vertical scanning movements. The laser beam from a femtosecond titanium:sapphire laser (80 MHz repetition rate, 120 fs pulse width, 780 nm central wavelength) was ightly focused by a high-numerical-aperture (NA=1.35) objective for 3D scanning to photocrosslink protein molecules within the focal spot and directly write out protein micro/nanostructures on the matrix. Here, kinds of microlenses (including refractive, diffractive and hybrid microlenses, etc.) as well as microlens arrays were conducted using protein aqueous ink. By carefully optimization, the single-line width of protein FsLDW could be tailored by changing the processing parameters and was as low as ~200 nm. Smooth surface with roughness average (Ra) of ~ 5-10 nm and outstanding 3D geometry were assured by optimized laser finishing resulting in excellent optical performances. PH value was chosen as the main environmental signal to tune the protein microlens in consideration of the possible operating environment, for example, microfluidic chips. The microlenses were fabricated in neutral protein aqueous ink, and swelled both in acidic and basic environment leading to the change of the curvature radius and hydrogel’s refractive index which then resulted into the adjustment of imaging and focusing. The microlenses performed well in an aqueous mixture of rabbit serum and red blood cells, which experimentally proved the good biocompatibility and ability of anti-biofouling of protein-based microelements.

8817-27, Session PWed

An efficiency method of synthesis to study the effect of annealing temperature on formation of calcium phosphates ceramics

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In recent years, there has been growing interest in studies of ceramic based on calcium phosphates, such as hydroxyapatite [(HAP) - $Ca10(PO4)6(OH)2$)] together with the β-tricalcium phosphate [(β-TCP) - $Ca3(PO4)2$]. In this work, biphasic calcium phosphate ceramics HAP/β-TCP was synthesized by solid state reaction, starting from calcium carbonate and ammonium phosphate monobasic for 10 h, with the goal of evaluating the influence of annealing temperature on the formation of ceramic materials. Samples synthesized at five different temperatures, 700, 800, 900, 1000 and 1100°C were investigated using the techniques of Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, Scanning electron microscopy (SEM), X-Ray Diffraction (XRD) and Rietveld refinement. From FTIR and Raman spectra, the presence of functional groups corresponding to phosphate (PO4)3- in all samples were observed. SEM measurements showed the presence of pores, important for potential biomedical applications, consequently favoring osseointegration. While, the XRD analyzes of the crystalline structures of these materials revealed the phases related to HAP and β-TCP. Finally, the quantification of phases obtained in x-ray difractograms was made using the Rietveld refinement. Our results indicate that increasing the annealing temperature leads to decrease in the percentage of phosphate β - tricalcium phosphate, and, therefore, according to the literature, the sample synthesized at 1100°C, with the proportions of HAP of 63.17% and 36.83% β-TCP, showed the better performance to applications. In addition, the method showed compares favourably to the current methods by its versatile, due to its simplicity of synthesis, and a short period of time to the heat treatment.

8817-29, Session PWed

Processing and nano-mechanical characterization of gold-chitosan nanocomposites for biomedical applications

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Gold nanoparticle reinforced chitosan bionanocomposite is excellent material for biosensors and certain implants. Nano-sized particle reinforcement into chitosan matrix enhances the materials properties and alters the microstructure. Naturally derived chitosan from shrimp shells was processed through acetic acid treatment to make the matrix of nanocomposites. Gold nanoparticles (~30 nm) were synthesized via citrate reduction method from HAuCl4 and incorporated in chitosan matrix. The bionanocomposite films were then prepared through solution casting with varying concentration of gold nanoparticles. Uniform distribution of gold nanoparticles was achieved throughout the chitosan matrix. Synthesis outcomes and prepared nanocomposites were characterized through SEM, TEM, EDS, UV-vis, zeta potential and FT-IR for their physical, morphological and structural properties. Materials response under the influence of temperature, frequency and indentation depth was characterized through various nanoindentation techniques. Quasi-static nanoindentation was used to determine elastic properties such as hardness and reduced modulus while dynamic nanoindentation was used for viscoelastic properties such as storage modulus, loss modulus, viscoelastic creep and relaxation of the nanocomposites. High temperature nanoindentation technique was used to investigate glass transition temperature of the nanocomposites. Through quasi-static nanoindentation, it was observed that the hardness and reduced modulus of nanocomposites increased significantly with direct proportion of gold nanoparticles concentration. Gold nanoparticles concentration showed positive impact on storage modulus and glass transition temperature of the materials. Lower storage modulus at higher indentation depth was recorded in all nanocomposites. In summary, the results show enhanced mechanical properties with increase in gold nanoparticles concentration and provide better understanding of structure-property relationships of such biocompatible materials for biomedical applications.

8817-30, Session PWed

Mesenchymal stem cells are differentiated by PEDF to osteoblasts in alginate microbeads

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Stem cell encapsulation has become a promising tool in the bone tissue engineering field. However, the major challenge of this technique is in the timing of cell differentiation and cell release into the desired bone defect area. In this study, we used the anti-angiogenic protein, pigment epithelium-derived factor (PEDF), as an osteogenic supplement to differentiate mesenchymal stem cells (MSCs) to osteoblasts in monolayer cell culture and encapsulated within alginate microbeads. We show that PEDF has osteogenic differentiation potential, using qualitative and quantitative methods (such as viability assay, immunocytochemistry, assays for mineralisation and immunoblotting). Alginate microbeads containing MSCs and PEDF degraded significantly more compared to alginate microbeads with MSCs alone, signifying that PEDF differentiates MSCs into osteoblasts that are capable of being released from entrapment within the bead matrix. Thus, stem cells encapsulated with PEDF within alginate microbeads are released as differentiated osteoblasts as assessed by immunostaining for alkaline phosphatase, collagen-1, osteopontin, and osteocalcin (major osteogenic biomarkers). PEDF is a promising protein candidate for supporting osteoblastic differentiation in enhancing bone tissue engineering.

8817-31, Session PWed

Effect of the surface plasmon on second harmonic generation from tyrosine

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The Second Harmonic response from biomaterials is at the focus of current fundamental studies. One of the reasons for this recent interest stems from the potential use of Second Harmonic for optical imaging of biological tissues. Aromatic as well as non aromatic amino acids have therefore been investigated in detail. In particular, their first hyperpolarizability has been determined by hyper Rayleigh scattering. Tryptophan and Tyrosine have thus been shown to potentially be interesting targets in peptides and proteins owing to their rather large first hyperpolarizability.

However, recent studies have also provided hints on the sensitivity of the first hyperpolarizability of these aromatic amino acids to perturbations, in particular to the complexation with metallic salts, like silver or gold salts. Besides, it is also known that metallic nanoparticles can provide large enhancement of electromagnetic fields in their immediate vicinity under Surface Plasmon excitation.

This work therefore reports the use of hyper Rayleigh scattering to measure the first hyperpolarizability of tryptophan and tyrosine in the close vicinity of small gold or silver metallic nanoparticles. A wavelength analysis in particular is helpful in determining the role of the Surface Plasmon resonance in the observed changes of the first hyperpolarizability of tryptophan and tyrosine.

8818-1, Session 1

Bioinspired superhydrophobic, self-cleaning and low drag surfaces *(Keynote Presentation)*

Bharat Bhushan, The Ohio State Univ. (United States)

Nature has developed materials, objects, and processes which function from the macroscale to the nanoscale. These have gone through evolution over 3.8 billion years. The emerging field of biomimetics allows one to mimic biology or nature to develop nanomaterials, nanodevices, and processes [1-3]. Properties of biological materials and surfaces result from a complex interplay between surface morphology and physical and chemical properties. Hierarchical structures with dimensions of features ranging from macroscale to the nanoscale are extremely common in nature to provide properties of interest. Molecular scale devices, superhydrophobicity, self-cleaning/anti-fouling, drag reduction in fluid flow, energy conversion and conservation, high adhesion, reversible adhesion, aerodynamic lift, materials and fibers with high mechanical strength, biological self-assembly, anti-reflection, structural coloration, thermal insulation, self-healing, and sensory aid mechanisms are some of the examples found in nature which are of commercial interest. This talk will provide a broad overview of four selected objects of interest found in nature and applications under development or available in the marketplace. These will include (1) Lotus Effect used to develop superhydrophobic and self-cleaning/anti-fouling surfaces with low adhesion [3-5], (2) Shark Skin to develop surfaces with low fluid drag and anti-fouling characteristics [3,6], and (3-4) Rice Leaf and Butterfly Wing Effect to develop superhydrophobic and self-cleaning/anti-fouling surfaces with low drag [7-8]. Rice leaf and Butterfly Wings combine the Shark Skin and Lotus Effect.

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8818-2, Session 2

Imprinted and injection moulded nano structured optical surfaces *(Invited Paper)*

Anders Kristensen, Alexander B. Christiansen, Jeppe Clausen, Emil Højlund-Nielsen, Claus H. Nielsen, Technical Univ. of Denmark (Denmark); Claus F. Hansen, Tommy Kristiansen, Erik L. Simonsen, Per Høvsgaard, LEGO Group (Denmark); N. Asger Mortensen, Technical Univ. of Denmark (Denmark)

Within the past decades, nano-structured surfaces, or sub-wavelength structures (SWS) have attracted much attention as a cost-efficient (non-vacuum) alternative to multi-layer thin film deposition for obtaining anti-reflective optical surfaces. In this paper, nanostructured polymer surfaces are fabricated by up-scalable polymer replication methods: imprinting/embossing and injection moulding. A Black Silicon (BSi) random nanostructure surface is used as master original. The optical transmission at normal incidence was measured for wavelengths from 400 nm to 900 nm. For samples with optimized nanostructures, the transmission was increased by 2% compared to samples with planar surfaces.

8818-3, Session 2

Use of modulated pulse power magnetron sputtering for the systematic variation of film stoichiometry at static reactive gas flow rates

Neil R. Murphy, Lirong Sun, John T. Grant, John G. Jones, Rachel Jakubiak, Air Force Research Lab. (United States)

Reactive modulated pulse power magnetron sputtering (MPPMS) was used in the deposition of multilayer metal-dielectric stacks from a single transition metal sputtering source under a static flow rate of reactive gas. The MPPMS technique allows the user to have precise control over the magnitude and frequency of the voltage pulses applied to the cathode. At the foundation of this method is the ability to form a dielectric compound on the surface on a metallic sputtering target in a low frequency regime and dynamically reduce it by applying a more aggressive, higher frequency voltage pulse.

Switching between dielectric and metallic target surfaces created alternating metal – dielectric layers without varying the flow rate of the oxygen and argon gases. Oxide impurity concentrations within the metallic layers were not large enough to inhibit the absorptive properties of the base metal. Material systems explored include oxides of molybdenum and tantalum. Optical characterization of the films was conducted using UV-visible spectroscopy and in situ spectroscopic ellipsometry. Experimentally obtained values for the wavelength dispersion of refractive index and extinction coefficient values were used in the design and prediction of the performance of multilayer interference filters.

8818-4, Session 2

Two-dimensional nanostructures on optical glass via nanosphere lithography and vapor HF etching

Elmer Wang, Wayne State Univ. (United States) and Visotek, Inc. (United States); Yang Zhao, Wayne State Univ. (United States)

It is desired to have artificial optical materials with controllable optical properties. One approach is to create composite materials with nanomachining and nanostructures. In this research, two-dimensional (2D) nanostructures were created on the surface of optical glass using nanosphere lithography. The effective refractive index of the artificial layer is smaller than the refractive index of the substrate and can be varied by changing the size of the nanoparticles and depth of etching. In comparison with conventional techniques, this approach is more efficient and cost-effective for the creation of large areas of thin surface layers as an artificial material. A uniform monolayer of 200 µm polystyrene nanospheres was deposited on soda-lime glass slides. Deposition was performed via a slide-coating technique to take advantage of capillary forces. The slides were etched with vapor-phase hydrofluoric acid (HF) to create 2D structures. Vapor-phase etching was selected in order to etch the substrate without disturbing the monolayer nanoparticle mask. The etching rate of nanostructures was studied. An atomic force microscope (AFM) was used to monitor the nanosphere monolayers and etching analysis. It was shown that the nanoparticle pattern was successfully transferred to the surface of the substrate. The resultant thin-layer of modified substrate serves as an artificial material with a desired refractive index which modifies the surface reflection and transmission properties. The substrate with the created artificial material layer demonstrated reduced reflectivity in optical wavelengths.

8818-5, Session 2

Tunable stoichiometry of SiOx-BaOy-BOz fabricated by multi-target PLD

John G. Jones, Chad M. Holbrook, Jonathan T. Goldstein, Air Force Research Lab. (United States); Lirong Sun, General Dynamics Information Technology (United States); Neil R. Murphy, Rachel Jakubiak, Charles E. Stutz, Air Force Research Lab. (United States)

Nanostructured thin-films of multiple oxide materials were obtained by using pulsed laser deposition (PLD) with independent targets consisting of SiO_2, Ba, and B. At a power of 300 mJ per pulse, island growth occurred on a per pulse basis with some 150 pulses required to deposit 1 nm of material. Programmable stoichiometry of multi-component or nanostructured thin-films was achieved by using a 248 nm KrF excimer laser, a galvanometer mirror system, and three independent target materials. The number of pulses on each target can be programmed with a high degree of precision. Trends in material properties were identified by systematically varying the stoichiometries of multiple nanostructured thin-films and comparing the resulting properties measured using in-situ spectroscopic ellipsometry, x-ray diffraction (XRD), and energy dispersive spectroscopy (EDS)(reliable with ~ 1 um of material thickness). Typically thin-films deposited by PLD at temperatures below 300 C are amorphous, however, crystallinity was obtained with post growth heat treatment and verified with XRD.

8818-6, Session 2

SiC multi-layer protective coating on carbon obtained by thermionic vacuum arc method

Victor Ciupina, Univ. Ovidius Constanta (Romania); Cristian P. Lungu, National Institute for Lasers, Plasma and Radiation Physics (Romania); Rodica Vladoiu, Danut Tiberius Epure, Gabriel Prodan, Univ. Ovidius Constanta (Romania); Corneliu Porosnicu, Ionut Jepu, National Institute for Lasers, Plasma and Radiation Physics (Romania); Marius Belc, Madalina Prodan, Cosmin Rosca, Iuliana M. Stanescu, Constanta Stefanov, Mirela Contulov, Aurelia Mandes, Virginia Dinca, Univ. Ovidius Constanta (Romania); Eugenia Vasile, S.C. Metav-Cercetare Dezvoltare S.A. (Romania); Valer Zaroschi, National Institute for Lasers, Plasma and Radiation Physics (Romania); Virginia Nicolescu, Ceronav (Romania)

SiC single-layer or multi-layer on C used to improve the oxidation resistance and tribological properties of C have been obtained by Thermionic Vacuum Arc (TVA) method. The 200nm thickness carbon thin films was deposed on glass or Si substrate and then 100÷500 nm thickness SiC successively layers on carbon thin film was deposed. The microstructure and mechanical characteristics of as-prepared SiC coating were investigated by Transmission Electron Microscopy (TEM), Energy Dispersive X-Ray Spectroscopy (EDS), Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD) and tribological techniques.

Samples containing SiC single-layer or multi-layer coating on carbon were investigated up to 1000oC. The results of thermal treatments reveals the increase of oxidation resistance with increase of the number of SiC layers. The mechanism of oxidation protection is based on the reaction between SiC and elemental oxygen resulting SiO_2 and CO.

The tribological behavior of SiC coatings was evaluated with a tribometer with ball-on-disk configuration from CSM device with 6mm diameter sapphire ball, sliding speed in dry conditions being 0.1m/s, with normal contact loads of 1N, 3N and 10N, under unlubricated conditions. The friction coefficient on SiC was compared with the friction coefficient on uncoated carbon layer.

Electrical conductivity of SIC coating on carbon was measured comparing the potential drop on the sample with potential drop on a series standard resistance in constant current mode. The electrical conductivity of SiC coatings was monitoring relative to the uncoated carbon layers at different temperatures.

8818-7, Session 3

Homogenization of a lattice of resonant scatterers

Didier Felbacq, Univ. Montpellier 2 (France); Emmanuel Kling, Sagem (France)

Metamaterials are artificial composite objects that are considered for their “effective behavior” that is hardly encountered in natural materials and to some extend tailorable. The effective behavior is the one that emerges in the limit where the wavelength is “much larger” than the period of the cell upon which the metamaterial is built. Typically, the order parameter is $\eta=d/\lambda$. One of the main issue in defining the effective parameters is that the size of the cell in current metamaterials is not that small as compared to the wavelength. This makes necessary to go beyond the usual 0th order of homogenization theory (in the small parameter η). Unfortunately, it is not always clearly stated in the physical literature that homogenization only makes sense as an expansion in power of η, which results in claims that an effective permittivity could match the Bloch spectrum for any frequency. In this work, we address a simple situation where a layer of point-like scatterers is considered. A complete asymptotic analysis is given that allows a clear delimitation of the homogenization regime. It is also shown that, in that situation, the effect of spatial dispersion are limited and are not a clue to the description of the effective scattering behavior of the structure.

8818-8, Session 3

Modes of interaction between nanostructured metal and a conducting mirror as a function of separation and incident polarization

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The optical resonances that occur in nanostructured metal layers are modulated in thin film stacks if the nanostructured layer is separated from a reflecting conducting layer by various thicknesses of thin dielectric. We have measured and modeled the optical response of interacting silver layers, with alumina spacer thickness ranging from a few nm to 50 nm, for s- and p-polarized incident light, and a range of incident angles. Standard thin film models, including standard effective medium models for the nanostructured layer, break down for spacer thickness below a critical threshold. For example with polarisation in the film plane in this material combination it occurs at around 10 nm of Al_2O_3. This arises from onset of hybrid modes between the two plasmonic layers. Three types of new modes are possible (a) a two-particle mode involving a particle and its mirror image (b) A Fano resonance from hybridisation of localized and de-localised plasmon modes(c) a Babinet’s core-(partial) shell particle with metal core-dielectric shell in metal [1,2]. For larger spacings thin film and effective medium models do apply. Variations in peak intensity arise then from spacing dependent phase modulation.

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8818-9, Session 3

An investigation into Voigt wave propagation for optical sensing

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In the nonsingular case of optical propagation in a linear, homogeneous, anisotropic, dielectric material, two independent plane waves, with orthogonal polarizations and different phase speeds, can propagate in a given direction. However, in certain dissipative biaxial materials there are particular directions along which these two waves coalesce to form a single plane wave. This coalescent Voigt wave represents the singular case. Most notably, the amplitude of Voigt waves are linearly dependent upon propagation direction. A porous nanostructured material is envisaged which does not itself support Voigt wave propagation. But when this porous material is infiltrated with a fluid containing an agent to be detected, the resulting homogenized composite material does support Voigt wave propagation. Furthermore, the directions along which Voigt waves propagate may be sensitive to the concentration of the agent to be detected. This sensitivity is explored theoretically, in order to establish the feasibility of an Voigt-wave based optical sensor.

8818-10, Session 4

Robust and durable polyhedral oligomeric silsesquioxane-based anti-reflective coatings with broadband quasi-omnidirectional properties

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Polymer-based anti-reflective coatings on glass pose major challenges for outdoor applications due to their incompatible mechanical and thermal properties. Here we demonstrate a durable, chemically and thermally stable polyhedral oligomeric silsesquioxane-based (POSS) anti-reflective moth's eye nanostructures on glass fabricated by double-sided nanoimprint lithography (NIL). These anti-reflective nanostructures exhibited excellent broadband and quasi-omnidirectional antireflective properties. An optimum POSS resist composition for nanoimprinting was formulated. Thermal free radical co-polymerization during nanoimprint lithography produced a uniform array of moth's eye nanostructures on both sides of a glass substrate with yields ~90-100%. The measured elastic modulus of the POSS thin-films is higher than or equal to the average elastic modulus of polymers used to fabricate anti-reflective coatings such as polydimethylsiloxane, polycarbonate, polystyrene, polyethylene terephthalate etc. The transmittance of the plane glass increased from 91.8% to 98.2% the POSS-based moth's eye anti-reflective nanostructures on both sides of the glass. A minimum reflectance of 1.2% as compared to 8.2% in case of plane glass was observed in the POSS-based moth's eye ARC glass. The Weighted Average Transmittance (WAT), that is indicative of the broad-band property of anti-reflection, showed that the WAT for the POSS-based moth's eye ARC glass was 96% as compared to 90.5% for plane glass. A quasi-omnidirectional transmittance is also observed from -50° to +50° of angles of incidence for the POSS-based moth's eye ARC glass. Furthermore, a series of ASTM-based tests on the imprinted structure showed strong adherence to glass, better hardness and mechanical strength with superior chemical and thermal stability.

8818-11, Session 4

Titania nano rice: a robust superamphiphobic film

Anand G. Venkatesan, Saman S. Dinachali, National Univ. of Singapore (Singapore) and A*STAR Institute of Materials Research and Engineering (Singapore); Sreekumaran Nair, Amrita Institute of Medical Science (India); Seeram Ramakrishna, National Univ. of Singapore (Singapore)

Rice-shaped TiO2 nanostructures are fabricated by electrospinning for creating a robust superamphiphobic coating on glass substrates. The as-fabricated TiO2 nanostructures (sintered at 500 ºC) are superhydrophilic in nature which upon silanization turn into superamphiphobic surface with surface contact angle (SCA) values achieved using water (surface tension, γ = 72.1 mN/m) and hexadecane (surface tension, γ = 27.5 mN/m) being 166° and 138.5°, respectively. The contact angle hysteresis for the droplet of water and hexadecane are measured to be 2° and 12°, respectively. Thus, we have successfully fabricated superior self-cleaning coatings that possess exceptional superamphiphobic property by employing a simple, cost-effective and scalable technique called electrospinning. Furthermore, the coating showed good mechanical and thermal stability with strong adherence to glass surface thus revealing the potential for real applications.

8818-12, Session 4

Optical simulations of biomimetic nanostructures and applications in energy and toxic sensing

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Many natural surfaces are texturized in the nano-scale to impart certain optical properties, such as anti-reflection, and wetting properties, such as superhydrophobicity in lotus. The cornea of the moths or wings of Cicada has tiny conical burls that reduce reflection (in moths) and increase transmission (in Cicada) of the surfaces. We have fabricated nano-tip (NT) structures on semiconductor (Si, GaAs, GaP, GaN) surfaces by a top-down type self masked plasma etching process involving a plasma of silane, methane, hydrogen and argon. We simulate and compare the optical properties of these nanotips against simple geometrical structures as single and dual diameter nanorods using FDTD. The anti-reflection properties are explained on the basis of gradient refractive index (GRIN) profiles of these structures. The plasma etching can be tuned with respect to substrate properties to arrive at superior surface designs meeting the application needs.

We have used the silicon nanotips (SiNTs) with a thin atomic layer deposited oxide coating to obtain thin film capacitors with the highest (till date) equivalent planar capacitance. The structure could be used as super-capacitors in energy-related devices.

Another application of these nanotips is in molecular sensing via surface enhanced Raman scattering (SERS). Optical sensing of DNA has been demonstrated at the sub-picomole level using self assembled silver nanoparticle (AgNPs) decorated gold nanotip (AuNT) arrays. We show how AgNP coated SiNTs can detect toxic molecules used as insecticides in agricultural products.

8818-13, Session 5

Liquid crystal optical fibers for sensing applications *(Invited Paper)*

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Propagation characteristics of optical fibers are greatly dependent on the material which the fiber is comprised of. Varieties of materials have been developed, and investigated for their usage in fabricating optical fibers

for specific applications. Within the context, a liquid crystal medium is both inhomogeneous and optically anisotropic, and fibers made of such mediums are greatly useful. Also, liquid crystals exhibit strong electro-optic behavior, which allows alternation in their optical properties under the influence of external electric field. These features make liquid crystal fibers to be of prudent use in the area of optics and photonics.

The present communication is aimed at providing a glimpse of the efficacy of liquid crystal fibers followed by the analytical investigation of wave propagation through such guides. Generally, transverse electric and transverse magnetic are the two types of modes that can be sustained in such guides; both of these modes are individually tackled to explore the propagation characteristics. The investigations reveal the novelty of the usage of liquid crystal fibers for optical sensing and/or field coupling under the situation when the transverse electric modes are excited in the guide. The case of tapered liquid crystal fibers is also discussed, and it is found that the tapering of the geometry greatly improves the propagation features so that these would be highly efficient for aforesaid applications. A control on the dispersion characteristics of such fibers may also be imposed by making the guide even more complex. The possibility of devising such options is also touched upon.

8818-14, Session 5

Waveguide core integrated nanostructured SERS sensor platform

Stuart J. Pearce, Swezin Oo, Michael E. Pollard, Ruiqi Y. Chen, Sumit Kalsi, Martin D. B. Charlton, Univ. of Southampton (United Kingdom)

The intensity of Raman scattering can be enhanced by a factor of 106 using Surface Enhanced Raman Spectroscopy (SERS). In this method, molecules are placed within a few nm of a rough/nanostructured metal surface. In this paper we show fabrication and characterisation of an integrated optical waveguide beneath a nano-structured precious metal coated surface. By using a waveguide core, the excitation field comes from underneath and enters the nanostructures at the base. This allows the emission to reach the discrete sensing areas effectively and should provide ideal parameters for maximum Raman interactions. The nanostructured geometry projects the Plasmon field into free space, thus increasing the cross section of interaction between the analyte molecules and optical fields, thereby increasing device sensitivity. Thin films of silicon oxynitride were deposited using PECVD on to thermal oxide coated 4 inch wafers and annealed at various temperatures to obtain low loss layers suitable for the waveguide core material. Based on the results from our simulations, nanostructured features of various diameters/feature lengths and pitch were etched into the low loss silicon oxynitride layer. The sensor area was coated with a thin layer of gold (25nm) and a variety of optical measurements were completed for many of the processed test chips including broadband reflectrometry, normal incident Raman spectroscopy and waveguide Raman spectroscopy using a Raman probe above the sensor area. The results showed that detection of a Raman active molecule (Benzyl Mercaptan) was possible when excited from the underlying waveguide core with 104 sensitivity.

8818-15, Session 5

Surface-plasmonic-polaritonic sensor using a dielectric columnar thin film

Stephen E. Swiontek, Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States)

Surface-plasmon-polariton (SPP) waves are electromagnetic surface waves exploited for real-time and label-free optical sensing of biochemical and chemical species in research and industrial settings. SPP waves are guided by the interface of a thin metal film and a substantially thicker dielectric material.

Theory shows that a SPP wave can be launched at the interface of a thin metal film and a dielectric columnar thin film (CTF) in the Turbadar-Kretschmann-Raether configuration. The CTF is an assembly of parallel and tilted nanowires grown by physical vapor deposition. A collimated vapor flux is generated and directed towards a substrate which is held at a fixed orientation in relation to the vapor flux. The CTF contains void regions which can be infiltrated with a fluid. The angular location of the SPP wave in the Turbadar-Kretschmann-Raether configuration will shift upon infiltration of the CTF by the fluid, and the device can behave like an optical sensor.

Therefore, a 30-nm-thick aluminum film was deposited onto an SF-11 glass substrate, followed by a partnering lanthanum-fluoride CTF. The sample was affixed to an SF-11 right-angle prism and the reflected intensities of a p-polarized plane wave at different angles of incidence were recorded. The angular location of the SPP wave was recorded in relation to: (i) the deposition parameters, (ii) the orientation of the CTF, and (iii) the refractive index of the infiltrant fluid.

8818-16, Session 5

Waveguide-mode sensors with sculptured porous waveguide

Motofumi Suzuki, Munehito Takagaki, Shohei Kuriyama, Kaoru Nakajima, Kenji Kimura, Kyoto Univ. (Japan)

Recently, so-called waveguide-mode sensors, which consist of multilayer of dielectric/absorptive/glass substrate, are attracting much attention from viewpoints of applications to the molecular detection. In order to enhance the sensitivity, open pores much smaller than the wavelength are introduced into the waveguide layers so that their effective refractive index changes depending on that of the surrounding fluid. The cost effective processes to create nanopores with high uniformity and reproducibility are strongly required. In this work, obliquely deposited thin films with nanocolumnar structures have been introduced to the waveguide layer in the waveguide-mode sensors. The multilayers including the porous SiO2 waveguide layer were prepared by dynamic oblique deposition technique. On a glass substrate, a Si layer as the absorptive layer was deposited by e-beam evaporation up to 240 nm thick from surface normal. A nanocolumnar SiO2 layer was deposited at a deposition angle of 70 degree by e-beam evaporation up to a thickness of 700 nm. The substrate was rotated rapidly during the deposition. The reflectance measured in the different fluid as a function of angle of incidence shows sharp minima. The angles of the reflectance minima depend strongly on the surrounding fluids of air, H2O and C2H5OH. Consequently, the nanocolumnar thin films are quite useful for the waveguide layer in the waveguide-mode sensors.

8818-17, Session 5

Influence of structural, morphological, and compositional aspects on NO2-sensing ability of TiO2-NTs

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In this work, nano-tubular TiO2 sensing-layers were synthesized through the anodization method. In order to improve the sensor ability (i.e. sensitivity, selectivity or response-recovery time) of TiO2-NTs, Cr-doping process was achieved by chemically-wall wetting route. The sensor properties (selectivity, sensitivity or response and recovery time) of un-doped and doped TiO2-NTs were carried out by DC-resistance measurement towards, NO2 and CO varied temperature of 300°C to 500°C. Moreover, the morphology (i.e thickness of TiO2-NTs), measurement temperature and doping effect on sensor behaviours were figured out by Electrochemical Impedance Spectroscopy (IES) with equivalent circuit model fitting

8818-18, Session 5

Enhancement in electrogenerated chemiluminescence technique using nano particles-thin film

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Simply put ECL or Electrogenerated chemiluminescence involves applying electric potential to a chemical reaction, resulting in the oxidation or reduction of the substance which reacts to produce light. The amount of analyte is ideally proportional to the amount of light detected so ECL can be used to measure the amount of a given chemical in solution. One of the important ways is based on modification of electrode surface using nano materials which enhance ECL signals compared to the unmodified electrode. In general, with regarding to works done in this topic, the nano particles can be immobilized on a appropriate support, such as nafion film or sol–gel film which were immobilized on the surface of electrode. Compared to the bare electrode, the modified electrode incorporating nano particles significantly enhanced the response of the ECL sensor due to the enhanced specificity of the modified electrode. As an example we used silver nanoparticles as part of modifier layers to enhance the sensitivity of obtained biosensor toward glucose determination. Compared to nanoparticles free biosensor, nanoparticles included biosensor shows huge sensitivity as well as more stability toward determination of glucose.

8818-37, Session PWed

Evolution of optical and plasmonic properties of aluminum/porous alumina thin films during anodization and etching processes

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Devices, based on surface plasmon resonance phenomena have a variety of sensing applications. Aluminum/ porous alumina based sensors attract much interest due to coupling of surface plasmon to waveguide modes, enhanced surface area of porous alumina, chemical and mechanical stability and ability to precisely control properties of the film by selecting anodization and etching conditions. In this work we carried out ellipsometry, SEM, and reflectometry measurements to study evolution of effective refraction index, thicknesses of the aluminum and porous alumina layers, porosity, reflectivity curves and surface plasmon resonance angle during anodization and etching and built theoretical models of these processes. Theoretical models along with Bruggeman approximation and Fresnel equations were used to calculate evolution of reflectivity curves and sensitivity. Results of calculations agree well with experimental measurements at all stages of the film manufacturing. Using theoretical modeling we determined optimal manufacturing conditions and film parameters that would guarantee maximal sensitivity at fixed wavelength.

8818-38, Session PWed

FDTD modelling of waveguide core integrated etched nanostructures

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Surface Enhanced Raman Spectroscopy (SERS) allows the intensity of Raman scattering to be enhanced by a factor of 106 by placing molecules within a few nm of a rough metal surface. In this paper we continue our investigation into a completely different configuration for a SERS sensor platform, incorporating an optical waveguide beneath a nano-structured precious metal coated surface. The nanostructured geometry projects the Plasmon field into free space, thus increasing the cross section of interaction between the analyte molecules and optical fields, thereby increasing device sensitivity. In this arrangement the excitation field comes from underneath and enters the nanostructures at the base. This allows the emission to reach the discrete sensing areas effectively and should provide ideal parameters for maximum Raman interactions. Using Finite Difference Time Domain (FDTD) modeling methods the waveguide coupled SERS nanostructures were fully analyzed and their theoretical performance simulated by using frequency domain power monitors around the nanostructures. The model investigates efficiency of coupling between the waveguide and surface plasmons, but also investigates spatial localization around sharp features of the geometry. Simulations were completed using different types of etched nanostructures (pryamidal, circular, square) and dimensions to determine a suitable sensor area which would allow for maximum field intensity within the features when excited from underneath. The simulations suggested that a pitch of 2500nm, a circular or square diameter/feature length of 500nm and an etch depth of 400nm showed more field intensity within the nanostructured pits.

8818-40, Session PWed

Self-organising formation of super layer Structure in PbBr-based layered perovskite superlatice materials by mixing of bulky chromophore-linked ammonium bromide and alkyl ammonium bromide

Masanao Era, Koich Sakaguchi, Saga Univ. (Japan)

A family of lead-bromide based layered perivskite [(RNH3)2PbX4] is a self-organized organic-inorganic surper lattce material, in which organic dielectric (RNH3) layer and tow-dimensional lead halide semiconductor layer consisting of cornar-sharing PbX6 ocatahedra are alternately piled up. Based on their low dimensional semicondctor nature (quatum well), they form stable exciton, and exhibit attractive optical properties, efficient photoluminescence, electroluminescence and efficient optical nonlinearity owing to the stable exciton. In this work, we found that the supuer lattice structure is albe to be modified by the ratio of chromophore-linked alkyl ammonium bromide, alkyl ammonium bromide and lead bromide PbBr2, which is dissolved in the solution employed for a simple spin-coating.

Propyl ammonium bromide 1, carbazole-linked and naphthalen-linked ammonium bromides 2 and 3, and PbBr2 4 were dissolved in dimethylformamide (DMF) at the molar ratio of 1:2:4 and 1:3:4 = 2:0:1, 4:2:3, 1:1:1, 2:4:3, and 0:2:1. The thin films were prepared on fused quartz substrates by spin-coating from the DMF solutions.

Super layer structure, where organic dielectric layer, inorganic semiconductor layer, and organic semiconductor are assembled in order, was successfully constructed by a simple spin-coating with the solution in which propyl ammonium bromide 1, carbazole-linked propyl ammonium bromide 2 and PbBr2 3 (the molar ratio; 1:2 :4 and 1:3:4=4:2:3) were dissolved. Detailed results will be presented in this presentation.

8818-41, Session PWed

IGZO oxide thin film transistors with 3-layer gate insulator

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In this study, we applied the 3 layer gate dielectrics to a-IGZO TFTs in order to display panel performance improvement, and also semiconductor active layer with protection layer (PL). The electrical measurements of the ZnO TFT devices were performed in ambient air

(room temperature and 20% relative humidity) without passivation using a Keithley 4200 semiconductor parameter analyzer. The device fabrication process involves a series of thin film deposition and photolithographic patterning steps. In order to minimize contamination, the substrates usually undergo a cleaning procedure using deionized water, before and after the growth of thin films by sputtering methods. The devices structure were fabricated top-contact gate TFTs using the a-IGZO films on the plastic substrates. The channel width and length were 80 and 20 um, respectively. The source and drain electrode regions were defined by photolithography and wet etching process. The electrodes consisting of Ti(15 nm)/Al(120 nm)/Ti(15nm) trilayers were deposited by direct current sputtering. The 30 nm thickness active IGZO layer deposited by rf magnetron sputtering at room temperature. The deposition condition is as follows: a rf power 200 W, a pressure of 5 mtorr, 10 % of oxygen [O2/(O2+Ar)=0.1], and room temperature. A 9-nm-thick Al2O3 layer was formed as a first, third gate insulator by ALD deposition. A 290-nm-thick SS6908 organic dielectrics formed as second gate insulator by spin-coating. The TFTs device has a channel width (W) of 80 µm and a channel length (L) of 20 µm. The IDS-VDS curves showed well-defined transistor characteristics with saturation effects at VG>-10 V and VDS>-20 V for the inkjet printing IGZO device. The carrier charge mobility was determined to be 15.18 cm^2 V-1s-1 with FET threshold voltage of -3 V and on/off current ratio 10^9

8818-42, Session PWed

Studies on nonlinear optical absorption of indium gallium zinc oxide (IGZO) thin films

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Amorphous oxide semiconductors (AOS)are of considerable interest for next generation optoelectronic device applications. One of the most promising AOS materials is indium–gallium–zinc–oxide (IGZO) which is being used as a channel layer in transparent thin film transistors.

N-type transparent conducting indium gallium zinc oxide (IGZO) films were successfully grown on glass substrates at room temperature by rf magnetron sputtering using a powder target. Structural, optical, morphological and electrical properties of IGZO films were investigated. Structural studies by X-ray diffraction showed that all IGZO films were amorphous in nature. The surface morphology of IGZO films analyzed by scanning electron microscope (SEM) and atomic forced microscopy, revealed that all the films are uniform and film deposited at 40W rf power have an average roughness of 0.75nm. Composition of the film was confirmed by EDAX measurement which shows that percentage of Zn increased with the increase of rf power. The average transmission in the visible range was greater than 80% and the transmission in the higher wavelength region decreased with increase in rf power. Refractive index in the visible region of IGZO film calculated by Swanepoel technique was found to be 1.92. The carrier concentration in IGZO films can be controlled by controlling rf power due to the increase of Zn/(Ga+In+Zn) ratio. Hall measurement shows a carrier concentration of 2.5e18 cm ?3 and conductivity 87.52S/cm for the films deposited at 100W rf power . The nonlinear optical absorption in IGZO thin films and its dependence on the free-carrier density using Z-scan technique has been investigated. It was observed that nonlinear absorption coefficient decreases with increasing carrier concentration.

8818-43, Session PWed

GaN-based light-emitting diodes by laser lift-off with Ag nanoparticles

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This study presents a GaN thin film light-emitting diode (TF-LED) on an electroplated flexible copper substrate to improve thermal conduction effect of the LED. The optoelectronic characteristics and stress effect of the GaN TF-LEDs on the electroplated flexible copper prepared by laser lift-off technique was examined.

The surface of the peeled GaN TF-LED after laser lift-off process demonstrated a pore array. The GaN pore array surface was etched by photo-electrochemical method to form hexagonal pyramid hillocks on the surface using KOH solution. Then, freestanding peeled GaN TF-LEDs with the front surface protected by wax were immersed into 3M KOH solution at room temperature for 30min under ultraviolet illuminations to perform the photo-electrochemical etching. A single-layer Ag film was deposited on a N-face GaN with pore array surface by RF magnetron sputtering. After 300 oC annealing, the Ag nanoparticles was formed on the roughened N-face GaN as a reflective layer for achieving an improved light extraction in GaN-based LEDs.

Surface morphologies with and without photo-electrochemical etching were observed by field emission scanning electron microscope (FESEM) (LEO 1530).

8818-44, Session PWed

Optimizing absorptance in nanostructured thin films

Tom H. Anderson, Dominykas Gustas, Tom G. Mackay, The Univ. of Edinburgh (United Kingdom)

Nanostructured thin films, such as chiral sculptured thin films (CSTFs) and columnar thin films (CTFs), are promising for a host of applications because their porosities and optical properties can be fine-tuned to order, at least up to a certain useful degree. One possible application lies in the area of dye-sensitized solar cells, wherein such nanostructured thin films may provide a scaffold to support light-absorbing dyes. A theoretical study is presented wherein CSTFs and CTFs are infiltrated with light-absorbing dyes. The structural parameters of the CSTFs and CTFs are varied in order to optimize absorptance. Results are compared against those for a simple porous isotropic dielectric material infiltrated with light-absorbing dyes. Conclusions are drawn about the feasibility of CSTFs and CTFs for applications requiring high absorptance, such as dye-sensitized solar cells.

8818-45, Session PWed

Size effect on negative refractive indexes of aluminum/silicon-dioxide/aluminum nanosandwich films

Yi-Jun Jen, Hung-Sheng Liao, Meng-Jie Lin, National Taipei Univ. of Technology (Taiwan)

In this study, three different thicknesses of aluminum (Al) / silicon-dioxide (SiO2) / aluminum (Al) nanosandwich films (SWFs) are deposited using glancing angle deposition (GLAD) technique with continuous azimuthal rotation. The SWF comprises the SiO2 layer sandwiched between Al nanopillars. The thicknesses d of top and bottom Al nanopillar increase from 188nm to 233nm. The thickness of SiO2 is fixed at 45nm. Each SWF is measured the reflection coefficients and transmission coefficients from its both sides by walk-off and polarization interferometers. By considering the bianisotropic parameter, the equivalent electromagnetic parameters of each film are derived from the four coefficients. The analysis of measured reflection and transmission coefficients of the SWF showed that it presents a negative-real equivalent permittivity as well as a negative-real equivalent permeability. Base on the analysis of measurement, the size effect of Al / SiO2 / Al SWFs is demonstrated for the optical properties. As the thickness d increase from 188nm to 233nm, the equivalent refractive index is negative and its average magnitude decrease from -1.703 to -1.247. The same trend can be found for the real part of equivalent permittivity varied from -1.193 to -0.824 with increasing thickness. Furthermore, the SWFs are also simulated to analyze the magnetic field in the SiO2 layer by finite-difference time-domain (FDTD). The result of simulation demonstrates the negative permeability comes from the reversed magnetic resonance within the SiO2 layer. The reversed magnetic field decreases with increasing thickness d.

8818-46, Session PWed

Success with an approach for computer-based numerical simulations

Diana Khashimova, Technische Univ. Hamburg-Harburg (Germany)

Zeolites are crystalline oxides with uniform, molecular-pore diameters of 3-14Å. Significant developments since 1950 made production of synthetic zeolites with high purity and controlled chemical composition possible. In powder-form, zeolites are major role-players in high-tech, industrial catalysis, adsorption, and ion exchange applications.

Understanding properties of thin-film zeolites has been a focus of recent research. The ability to fine-tune desired macroscopic properties by controlled alteration at the molecular level is paramount. The relationships between macroscopic and molecular-level properties are established by experimental research. Because generating macroscopic, experimental data in a controlled laboratory can be prohibitively costly and time-consuming, reliable numerical simulations, which remove such difficulties, are an attractive alternative.

Numerical models were developed for pure component and subsequently multicomponent adsorption processes. Using a Configurational Biased Monte Carlo (CBMC) approach in grand canonical ensemble, both process types were simulated numerically, replicating benchmark experimental data. Classical theoretical models using ideal (IAST) and real adsorbed solution theory (RAST) to predict mixture adsorption in nanopores, are also presented for comparison.

Reported are computer simulations for the adsorption of alkanes in the all-silica MFI (channel) and DDR (cage) type zeolites matching experimental data on adsorption of light hydrocarbons - alkanes- such as methane, ethane and butane. Included are binary and ternary mixtures.

The numerical approach developed can be a powerful, cost and time saving tool to predict process characteristics for different molecular-structure configurations. The approach used here for simulating adsorption properties of nanopore materials including process characteristics, may have great potential for other properties of interest.

8818-19, Session 6

Tailoring optical complex fields with nanostructured metallic thin film *(Invited Paper)*

Qiwen Zhan, Univ. of Dayton (United States)

Polarization of light plays an important role in optical science and engineering. Recently there is an increasing interest in complex optical fields with spatially inhomogeneous state of polarizations and optical singularities. New effects and phenomena have been predicted and observed for light beams with these unconventional states. In this talk, I will first review the recent developments in complex optical fields and their potential applications. A summary of methods for the generation of these fields will be provided. Among various generation techniques, nanostructured metallic thin film offers unique advantages due to its compactness and flexibility. Furthermore, strong interactions of nanostructured metallic film with vectorial optical fields enable the development of unique functional devices and systems. As examples, the design and fabrication of nanostructured metal thin film that can produce complex vector fields for focal field engineering (specifically for optical needle field generation) will be presented. Beaming and steering of photons emitted from nano-emitters integrated with nanostructured metal thin film will be demonstrated. The design of a plasmonic metal-insulator-metal (MIM) device that integrates several functions will also be illustrated.

8818-20, Session 6

Collective phenomena in plasmonic nanostructures and photonic metamaterials *(Invited Paper)*

Stefan Linden, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

Metamaterials have added new and fascinating effects to optics, e.g., magnetism at optical frequencies, negative index materials, and strong chirality. For most photonic metamaterials, the mesoscopic origin of these phenomena is the excitation of plasmonic modes in its metallic metaatoms. Thus, a qualitative first understanding of the features of a given metamaterial can often be obtained by considering the plasmonic resonances of an isolated metaatom. However, electromagnetic interactions between the metaatoms can have a significant impact on the properties of the metamaterial.

In this presentation, we will present recent experiments which underline the importance of collective phenomena in photonic metamaterials.

8818-21, Session 6

Multiply stacked ZnO nanoflowers by atmospheric plasma surface modification for flexible electronics

Do Yeob Kim, Jae Young Kim, Clemson Univ. (United States); Hyuk Chang, Youngjun Park, Samsung Advanced Institute of Technology (Korea, Republic of); Min Su Kim, Jae-Young Leem, Inje Univ. (Korea, Republic of); John Ballato, Sung-O Kim, Clemson Univ. (United States)

ZnO nanostructures with high surface area to volume ratio have shown great promise for sensors and energy harvesting applications. Here we demonstrate a simple approach for morphology-controlled bilayer ZnO nanostructures on plastic substrates derived from the surface modification of ZnO seed layers using an atmospheric pressure plasma jet (APPJ) treatment. Several advantages are expected from the plasma treatment on ZnO seed layers: (i) the surface wettability of the seed layers changes from hydrophobic to hydrophilic, resulting in higher surface energies for the growth of high-density ZnO nanostructures, (ii) the nucleation sites increase due to the increased surface roughness by the plasma etching, and (iii) there is no thermal damage to the plastic substrate by plasma treatment due to its low temperature weakly-ionized discharge. The obtained ZnO nanostructures consisted of a two-layered structure with nanorod arrays on the bottom layer and nanoflower arrays on the top layer. The individual nanoflower structure was composed of a number of hexagonal nanorods, which grew radially in many directions. Multiple-stacks of nanoflowers were grown continuously on the nanorods in the plasma-treated sample whereas only one stack of nanoflowers was grown on the nanorods in the as-prepared sample. It was confirmed that the plasma treatment induced a significant increase in the height and density of the ZnO nanoflowers/nanorods while the crystal shape and size of the ZnO nanoflowers/nanorods were barely affected. The multiply-stacked high-density ZnO nanoflowers/nanorods are easily obtained through a simple plasma treatment of the seed layer during conventional hydrothermal synthetic procedures making APPJ a very useful enhancement for flexible electronics on plastic substrates.

8818-22, Session 6

Nanostructured composite thin films with tailored resistivity by atomic layer deposition

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We have developed a new type of nanostructured composite material comprised of M:Al2O3 (where M= W or Mo) consisting of conducting metal nanoclusters embedded in an insulating Al2O3 matrix. These nanocomposite thin films were prepared by atomic layer deposition (ALD). Quartz crystal microbalance (QCM) measurements performed using various M cycle percentages revealed that the M ALD inhibits the Al2O3 ALD and vice versa. Despite this inhibition, the relationship between M content and M cycle percentage was close to expectations. Depth profiling X-ray photoelectron spectroscopy (XPS) showed that the (M:Al2O3) films were uniform in composition and contained Al, O, and metallic M as expected, but also included significant F and C. Cross sectional TEM revealed the composite film structure to be metallic nanoparticles (1-3 nm) embedded in an amorphous insulating matrix. The resistivity of these composite films could be tailored in the range of 1012-104 Ohm-cm by adjusting the M ALD cycle percentage. We have used these nanocomposite films as resistive coatings in microchannel plates (MCPs) fabricated from borosilicate glass micro-capillary capillary arrays manufactured by Incom, Inc. We have successfully demonstrated ALD MCPs up to 8” x 8” in size. These devices have application as image-preserving electron multipliers in a wide variety of applications. We have also utilized our M:Al2O3 nanostructured composite films as charge-drain coatings on the insulating components of electron- and ion-optics devices. Some of these applications will be highlighted in the presentation.

8818-23, Session 6

Optimization of a 2D-photonic crytal structure for light extraction in luminescent TiO2 thin films

Lucie Devys, Géraldine Dantelle, Ecole Polytechnique (France); Henri Benisty, Institut d’Optique Graduate School (France); Thierry Gacoin, Ecole Polytechnique (France)

Optimization of light propagation in optically active devices is the subject of large amount of works, motivated by applications in the field of photocatalysis, solar cells, OLEDs …The objective of our work is to characterize and optimize the extraction of a guided light in a high index luminescent thin film, using a 2D-photonic crystal imprinted on the film surface. For that purpose, we investigate a model system made up of two successive TiO2 layers obtained by sol-gel chemistry: the first one contains a dispersed luminescent non-scattering europium molecular complex, chosen for its large Stokes shift. The second TiO2 layer, deposited on top of the first one, is patterned on its surface by nanoimprint lithography. The patterning has a square geometry with a period of 400 nm and variable depth controlled by the viscosity of the TiO2 sol. The patterned area shows a 8-fold extraction enhancement compared with the unpatterned one. However, a key parameter to control extraction issues is the extraction length, corresponding to the length of light propagation in the film before being extracted. Using an optical microscope, we measure the extraction length with different depths of the surface structure: 20, 40 and 60 nm. By fitting the experimental results with the corresponding simulation, the extraction length is deduced, confirming that, in this range, the deeper the surface structure, the shorter the light extraction. Moreover the contributions of the extraction due to the crystal photonic and to the isotropic scattering linked to the imperfections of the layer are estimated.

8818-24, Session 6

Electrochemical deposition p-CdS nanowires

Maarif A. Jafarov, Baku State Univ. (Azerbaijan)

One-dimensional (1D) semiconductor nanostructures have received much attention due to their novel properties and potential applications in nanoscale electronics and optoelectronics. It is evident that the p-CdS nanowires with a smooth surface and a high aspect ratio still inside the nanochannels of anodic alumina substrate (AAS) can be clearly seen. The diameters of the nanowires are uniform and equal to the pore size of the AAS used.

One can see that the nanowire is dense and uniform in diameter corresponding to the pore size of the AAS. It is noticed that there are some contrast variations along the nanowires. The electrochemical deposition was carried out at a constant current density of 10 mA/cm2 at 330 K. During the pulsed time, species were reduced on the pore ground. The delayed time provided time for the recovery of the ion concentration. Here both the pulsed time and delayed time were 100 ms. The electrolyte was prepared by dissolving 1,0 mM CdCl2, 3.07 mM Na2S2O3, 0.15 M C6H8O7?H2O, and 0.05 M Na3C6H5O7x2H2O in water. The pH of the final electrolyte was adjusted to 5 with H2SO4.

Power X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM, H-800) and high-resolution transmission electron microscopy (JEOL-2010) were used to study the crystalline structure and morphology of nanowire arrays. The chemical compositions of the nanowires were determined by energy dispersive spectrometer (EDS). The band structure of the nanowires was obtained by measuring the optical absorption spectra on UV-visible spectrophotometer. For XRD and optical absorption measurements, the overfilled nanowires on the surface of the AAS and the back Au film were mechanically polished away using Al2O3 nanopowders.

It can be seen that the absorption spectrum of the p-CdS nanowires/AAS assembly system is quite different from that of the blank AAS, which is due to the absorption of p-CdS nanowires. The band gap of nanowires with diameters of 60 and 40 nm is about 3.4 and 3.5 eV, respectively. The shift of 40 nm nanowires is higher than that of 60 nm nanowires. This result indicates that the optical band edge of the p-CdS nanowires embedded in AAS exhibits a marked blue shift with respect to that of the bulk and thin-film p-CdS (2.4-2.5 eV). The blue shift could be attributed to the quantum size effect, which has also been observed in other semiconductor nanosystems. To obtain a high-filling, uniform, and single-crystalline p-CdS nanowire array by the electrochemical deposition into the nanochannels of the AAS, several factors should be considered. First, before electrodeposition the AAS should be ultrasonicated in water for a few minutes to remove the impurities and air bubble inside the nanochannels, because the p-CdS ions will preferentially nucleate and grow at the sites of the impurities, causing the inhomogeneous growth of nanowires, and the air bubbles will hinder the ions to diffuse into the nanopores of the AAS, causing the electrodeposition on the surface of the AAS. Second, a suitable deposition rate is critical to obtain dense, ordered, and single-crystalline nanowires. To avoid the rapid nucleation and growth and inhomogeneous concentration gradient in the nanopores, the pulsed electrodeposition technique is employed, which allows a better control over the deposition parameters, such as deposition rate and ion concentration at the deposition interface, as compared with the direct and alternating current deposition. The delayed time (100 ms) provided enough time for the concentration of the metal ions at the pore tips to achieve steady state through diffusion. No evident concentration gradient near the reaction interface exists during the deposition, and the pulsed time controls the atom-by-atom deposition of nanowires, which improves the homogeneity of the deposition and makes the deposited nanowires have a highly preferential orientation and good crystallization. Proper choice of the pH value of the electrolyte and deposition potential is also important.

8818-25, Session 7

Light-harvesting scheme employing nanostructured thin films for solar cells

Hsin-Ping Wang, Jr-Hau He, National Taiwan Univ. (Taiwan)

It is of current interest to develop the photon management with nanostructures since the ability to suppress the reflection and light trapping over a broad range of wavelengths and incident angles plays an important role in the performance of optoelectronic devices, such as photodetectors, light-emitting diodes, optical components, or photovoltaic systems. Superior light-trapping characteristics of nanostructured thin films, including polarization-insensitivity, omnidirectionality, and broadband working ranges are demonstrated in this study. These advantages are mainly attributed to the subwavelength dimensions of the nanowires, which makes the nanostructures behave like an effective homogeneous medium with continuous gradient of

refraction index, significantly reducing the reflection through destructive interferences. The relation between the geometrical configurations of nanostructures and the light-trapping characteristics is discussed. We also demonstrated their applications in a variety of solar cells. This report paves the way to optimize the nanostructured optoelectronic devices with efficient light management by controlling structure profile of nanostructures.

8818-26, Session 7

Modeling and comparison of light trapping caused by textured interfaces and nanoparticles in thin film solar cells

Birhanu Tamene Abebe, Erlangen Graduate School in Advanced Optical Technologies (Germany) and Friedrich-Alexander Univ. Erlangen-Nürnberg (Germany); Kai Hertel, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany) and Erlangen Graduate School in Advanced Optical Technologies (Germany); Christoph Pflaum, Erlangen Graduate School in Advanced Optical Technologies (Germany) and Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

The efficiency of thin film solar cells can be improved by various known and extensively studied light trapping techniques such as textured interfaces, nanoparticles, and so on. All these methods are expected to differ in the amount by which they improve the efficiency of the solar cells. In this paper, textured interfaces and nanoparticles are simulated and their respective effect on the absorption of the active layer, aSi:H in this case, is observed. The nanoparticles are silver nanoparticles, and for the interface simulations, a number of different AFM scans is used. For the nanoparticle simulations, different sizes, shapes and positions are simulated. To achieve this, Maxwell's equations are solved with a Finite Difference Method (FDM) and the Finite Integration Techniques (FIT) using a special scheme that accounts for the negative permitivity of silver. To accurately simulate the silver nanoparticles, the simulation is done with a very fine spatial discretization and run on high performance machines with a highly parallel iterative scheme. Before the two light trapping methods are implemented on the solar cells, their respective scattering behavior is determined by implementing the nearfield to farfield transformation using Fourier analysis.

8818-27, Session 7

High effective carrier lifetime of hierarchical structures by defect-removal etching for silicon heterojunction solar cells

Hsin-Ping Wang, Tzu-Yin Lin, National Taiwan Univ. (Taiwan); Ming-Yi Huang, AU Optronics Corp. (Taiwan); Jr-Hau He, National Taiwan Univ. (Taiwan)

Surface passivation is an important issue in a-Si:H/c-Si based heterojunction solar cells. To obtain desirable surface passivation, the surface area should be as small as possible (e.g., flat surface). However, because of the high reflective index of Si, the flat surface of Si causes up to 40 % of the incident light reflected, which severely limits device performances. Fabricating nanostructure is an effective way to reduce the reflection of light for solar cells but also aggravates the surface recombination by increasing the surface area. Therefore, a crucial challenge in heterojunction solar cell is to break the balance between surface recombination and light absorption losses.

In this work, the uniform compound structures were performed using metal-assisted chemical etching technique. Combined with defect removal etching (DRE), the reflectance was measured and the defect or contamination on the surfaces was monitored through the minority carries lifetime measurements and XPS measurement. The results shows that the reflectance is significantly suppressed, and the carrier lifetime would slightly reduce by controlling the morphology of nanostructures.

8818-28, Session 8

Roughness, optical, and wetting properties of nanostructured thin films *(Invited Paper)*

Angela Duparré, Sven Schroeder, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The talk will provide an overview on our measurement and analysis methodology to investigate the properties of thin film coatings related to their nanostructures and roughness. It will be shown that an unambiguous, comprehensive, yet handy assessment of nanoroughness can be accomplished on the basis of Power Spectral Density functions (PSD) and rms roughness parameters relevant for the specific function of the thin film component. Atomic force microscopy data of the film and substrate surface structures are combined with white light interferometry as well as light scattering techniques. Even though light scattering from thin film nanostructures is typically seen as an unwanted effect, it also carries valuable information about its origins. Compared to other characterization methods, scattering techniques are at the same time non-destructive, fast, and capable of investigating even large sample areas. The talk will also demonstrate how nanostructures that are essential for superhydrophobic and hydrophilic thin films can be predicted, characterized, and related to their functional properties. Examples of application comprise optical and non-optical thin films with different material compositions, designs, and nanostructures.

8818-29, Session 8

Optical property of obliquely deposited dielectric films upon a metamaterial thin film

Yi-Jun Jen, Meng-Jie Lin, Jia-Wei Dai, National Taipei Univ. of Technology (Taiwan)

The equivalent electromagnetic parameters of a silver nanorod array (Ag NRA) fabricated by glancing angle deposition are rederived by considering the bianisotropic parameter in additional to permittivity and permeability. The corresponding optical constants including refractive index, forward impedance and backward impedance are derived to present the wave propagating through the film. In measurement, the reflection coefficients and transmission coefficients from both sides of the Air/Ag NRA/ BK7 glass system are detected via walk-off interferometer. The equivalent optical constants are adopted to estimate the optical performance when additional films are deposited upon the NRA.

The Ag NRA is deposited at a deposition angle of 89deg first. A SiO2 NRA is then deposited at a deposition angle of -89deg. Finally a Ta2O5 NRA is deposited upon the SiO2 NRA at a deposition angle of 80deg. The reflectance and transmittance of the three-layered system Air/ Ta2O5 NRA (165nm)/ SiO2 NRA (133nm)/ Ag NRA(130nm) /BK7 glass are measured and compared with theoretical estimation of reflectance. At a wavelength of 568nm, the theoretical estimated the p-polarization reflectance is 21.75% that is close to the measured reflectance of 20.3%. On the other hand, it is demonstrated that suitable arrangement of dielectric thin films upon a metamaterial thin film can induce the p-polarized transmission.

8818-30, Session 8

Morphological and structural investigation of alpha-sexithiophene grown on KCl (100)

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Alpha-sexithiophene was deposited on KCl (100) by hot wall epitaxy technique [1] at different substrate temperatures (60°C – 135°C).

The morphological investigation was performed by AFM and optical microscopy, revealing terraced islands and needle-like anisotropic structures. It could be shown that needle formation is a thermally activated behaviour.

Structural investigations were performed by specular XRD scans. Upright standing molecules have been detected, which could be related to the terraced islands ((001) crystal contact plane). Furthermore, (010) and (-411) crystal planes have been observed, which explains the observed nano-needles (flat lying molecules).

The texture was investigated by XRD pole figures, showing that all three crystal types exhibit a well defined azimuthal alignment with respect to KCl high symmetry directions. Interestingly, the epitaxial orientation of the islands could be explained by "ledge directed epitaxy" [2], which describes the nucleation of crystallites on existing topographic features on the substrate (nano-needles).

A real space model of the crystallites was developed with the help of XRD pole figures and single crystal data. Surprisingly, the azimuthal orientation of the molecules is exactly the same for needles with (010) and (-411) contact planes. This observation represents a hint that the adsorption geometry of single molecules seems to be decisive for the organic crystal nucleation. Additionally, the substrate surface symmetry is nicely reflected by the multiplicity of formed needle orientations.

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[2] P.W. Carter, M.D. Ward, J. Am. Chem. Soc. 115 (1993) 11521-11535

8818-31, Session 8

Broadband and wide angle light absorption for an aluminum nanorod array in a prism-coupling system

Yi-Jun Jen, Jia-Wei Dai, Jung-Hui Chao, National Taipei Univ. of Technology (Taiwan)

Traditional optical thin films exhibit low absorption when light is incident obliquely because the optical path decreases with increasing angle of incidence. A thin light absorber is also a challenge to perform high absorption at oblique incidence. Under the condition of total reflection, a thin silver film with thickness around 40nm in a Kretschmann configuration (prism / metal film/ air) enables to absorb light at an extremely small angle range by exciting surface plasmon at interface of metal/air. In this work, a metamaerial thin film composed of aluminum nanorods is fabricated and used to absorb light in high efficiency.

Al NRA is 184nm thick and tilted at an angle of 40 with respect to surface normal. The deposition plane defined by the directions of rod and surface normal is orientated at angles of a=0 deg, a=90 deg, and a=180 deg with respect to the plane of incidence to measure the reflectance versus incident angles from 40 deg to 70 deg and wavelengths from 400nm to 700nm.

When the deposition plane is the same with plane of incidece, the reflectance spectra indicate that Al NRA exhibits strong absorptance over 80% at angles of incidence from 40 deg to 55 deg for both p-polarization and s-polarization. The enhanced p-polarized absorbtance is extended from 40 deg to 70 deg. At a=90 deg, the absroptance is weaker at angles of incidence from 55 deg to 70 deg compared with other two cases measured at a=0 deg and a=180 deg.

8818-32, Session 8

In situ stress evolution of the silver films on different seeding layers

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The in situ stress evolution of the thin silver films prepared using DC magnetron sputtering (DCMS) and modulated pulse power magnetron sputtering (MPPMS) techniques was measured in real time during the film growth using a high resolution multi-beam optical sensor (MOS). Simultaneously, in situ spectroscopic ellipsometry data was collected and correlated with the MOS data. The MOS is an extremely sensitive and non-destructive tool to measure thin film stress and interface effects during film growth. During deposition of silver on a Si substrate the compressive stress decreased from 7.2 GPa at 10 nm thickness to 2.5 GPa when the film thickness reached 20 nm. When silver was deposited on a ZnO film compressive stress was present initially, but switched to tensile stress around 7 nm indicating coalescence of the silver film. Earlier onset of coalescence of the thin silver films deposited on ZnO can be attributed to smaller and more prevalent nucleation sites that decreased the probability for large island growth compared to the Si. The in situ results were further correlated with the surface roughness, grain sizes and morphology by the XRD, XRR, XPS, AFM and SEM measurements for various seeding layers.

8818-33, Session 9

Thermal infrared emitters by plasmonic metasurface *(Invited Paper)*

Junichi Takahara, Yosuke Ueba, Osaka Univ. (Japan)

Recent progress of our study about thermal radiation from periodic microstructures on metal surface "metasurface" is reviewed. Modification of thermal radiation spectra is observed by resonant electromagnetic modes inside single micro-cavity fabricated on tungsten. In addition, new types of narrow-band thermal emitter using spoof-surface plasmon mode on a periodic array of micro-cavity is proposed. Finally, thermal radiation from metasurface composed in sprit-ring resonators is reported. These emitters are tunable on resonant frequency by structural parameters and can be applied to wide-range of emitting device from THz to IR range.

8818-34, Session 9

Gap surface plasmon resonators, antennas, and structures for plasmon nanofocusing *(Invited Paper)*

Dmitri K. Gramotnev, Nanophotonics Pty Ltd. (Australia); Anders Pors, Michael G. Nielsen, Sergey I. Bozhevolyi, Univ. of Southern Denmark (Denmark)

Plasmonic antennas and resonators, i.e., metal nanostructures exhibiting efficient (resonant) scattering of radiation and strongly enhanced local electromagnetic fields, offer unique opportunities for potential applications as plasmonic nanosensors, nanomanipulation and near-field trapping techniques, high-resolution probes for nanoimaging, improved photovoltaics, nanoscale photodetectors with significantly enhanced signal-to-noise ratio, catalysis applications, etc. This paper will analyze a new type of nanoantennas and resonators using gap surface plasmons (GSPs) in metal-insulator-metal configurations where only the top metal layer is structured. The analyzed configurations include circular GSP bowtie structures with large bow angles and strip-like continuous layer GSP resonators. The excitation of the plasmonic resonators is achieved through their illumination by the linearly polarized incident light. The analysis is based on rigorous numerical simulations and determination of the local field enhancements and scattering/absorption cross-sections. Spectral characteristics of the GSP bowtie structures are studied, demonstrating the existence of two distinct types of resonant modes with the domination of the dipole and quadrupole moments resulting in low- and high-Q resonances, respectively. The continuous layer GSP resonators in the form of metal stripes on a dielectric-metal layered structure are investigated numerically and experimentally, demonstrating good agreement between the experimental and theoretical results, excellent resonant characteristics, and significant levels of local field enhancement. The opportunities for a combination of nanoantenna resonant effects with plasmon nanofocusing in bowtie-like structures is also discussed and analyzed. The considered structures offer significant new potentials for the design of photovoltaic applications, nano-optical sensors, and devices with enhanced imaging, photodetection and nanomanipulation opportunities.

8818-35, Session 9

Large scale and low-cost fabrication of Fano-resonant plasmonic and photonic nanostructures for sensing

Benjamin Gallinet, Laurent Davoine, Guillaume Basset, Marc Schnieper, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

Nanostructuring of surfaces has recently become the cornerstone of many growing fields of nanoscience and technology, such as nanoelectronics, nano-electromechanical systems, plasmonics, and metamaterials. New patterning techniques are required to fulfil their meticulous fabrication requirements in terms of resolution, complexity, cost-efficiency, and throughput. We report on the fabrication by nanoimprint lithography of large-area plasmonic and photonic sensing platforms. Resonant gratings are obtained by patterning a sol-gel material and evaporating a high refractive index semiconductor. A chemically sensitive dye layer is deposited, which acts as the transducer. By exposition to a liquid or an invisible gas such as ammonium, the change in absorption is detected optically. An analytical model is introduced to explain the enhancement of the signal by the resonant grating, which can be detected with the naked eye from a color change of the reflected light. The sensors are compatible with environments where electricity cannot be used such as hospitals, industries, with explosives, and in traffic. The same fabrication procedure is used for metallic subwavelength structures supporting localized surface plasmons. The near-field and far-field optical properties of the system are investigated with an analytical model together with numerical calculations. The strong coupling between the different metallic layers leads to the formation of subradiant and superradiant modes, with the spectral signature of Fano resonances. Fano-resonant systems combine strong nanoscale light confinement with a narrow spectral line width, which makes them very promising for biochemical sensing and immunoassays, towards the label--free detection of single molecules in real time.

8819-1, Session 1

Controlling high-throughput manufacturing at the nano-scale *(Invited Paper)*

Khershed P. Cooper, U.S. Naval Research Lab. (United States)

Interest in nano-scale manufacturing R&D is growing. The reason is to accelerate the translation of discoveries and inventions of nanoscience and nanotechnology into products that would benefit industry, economy and society. Ongoing research in nanomanufacturing is focused primarily on developing novel nanofabrication techniques for a variety of applications—materials, energy, electronics, biomedical, etc. Our goal is to foster the development of high-throughput methods of fabricating nano-enabled products. Large-area parallel processing and continuous processing are high-throughput means for mass production. An example of large-area processing is step-and-repeat nanoimprinting, by which nanostructures are reproduced again and again over a large area, such as a 12 in wafer. Roll-to-roll processing is an example of continuous processing. By this means it is possible to print and imprint multi-level nanostructures and nanodevices on a moving flexible substrate. The big pay-off is reduced unit cost. However, the anticipated cost benefits can only be realized if the increased production rate is accompanied by high yields of high quality products. To ensure product quality, we need to design manufacturing systems such that the processes can be closely monitored and controlled. One approach is to bring cyber-physical systems (CPS) concepts to nanomanufacturing. CPS involves the control of a physical system such as manufacturing through modeling, computation and communication. Such a closely coupled system will involve in-situ metrology and closed-loop control of the physical processes guided by physics-based models, driven by appropriate instrumentation. This paper will discuss these ideas in the context of controlling high-throughput manufacturing at the nano-scale.

8819-2, Session 1

Inkjet-printed zinc tin oxide transport layers in inverted organic solar cells

Eric Danielson, The Univ. of Texas at Austin (United States); Harish Subbaraman, Omega Optics, Inc. (United States); Ananth Dodabalapur, The Univ. of Texas at Austin (United States)

Inverted organic solar cells, which utilize a transparent cathode and a high work function metal anode, have been the subject of extensive research. Their advantages over conventional organic solar cells include increased resistance to environmental degradation and compatibility with large area fabrication techniques. Carrier transport layers are essential for achieving high power conversion efficiencies in inverted organic solar cells and therefore need to be compatible with large area fabrication techniques. Inkjet printing is one such technique that can be integrated into the low cost, mass production of these cells via roll to roll fabrication. N-type metal oxides such as ZnO or zinc tin oxide (ZTO) have been used as electron transport layers for inverted cells, but only as spin coated films. We have developed inkjet printable ZnO and ZTO solutions for use as electron transport layers in inverted organic solar cells and achieved power conversion efficiencies of over 3% in inverted P3HT:PCBM solar cells with inkjet printed ZTO layers. We characterize these inkjet printed films using n-FET measurements and a variety of metrology techniques including AFM and ellipsometry. Printed ZTO film characteristics are compared with the resulting inverted solar cell performance and an optimal printing methodology is presented. We also incorporate inkjet printed PEDOT:PSS as a hole transport layer using previously established techniques to demonstrate the feasibility of large area inverted solar cell fabrication.

8819-3, Session 1

High precision dynamic gap control for optical nano-lithography using interferometeric-spatial-phase-imaging

Xiaolei Wen, Purdue Univ. (United States) and Univ. of Science and Technology of China (China); Luis Traverso, Purdue Univ. (United States); Pornsak Srisungsitthisunti, King Mongkut's Institute of Technology (Thailand); Euclid E. Moon, Massachusetts Institute of Technology (United States); Xianfan Xu, Purdue Univ. (United States)

In optical near-field nano-lithography, it is essential to achieve a high precision dynamic control over the distance between the optical mask and the substrate, which is about 10 nm. For this reason, we demonstrate the use of interferometeric-spatial-phase-imaging (ISPI) to control the gap distance. The ISPI technique creates interference fringes from checkerboard gratings fabricated on an optical mask, which are used to determine the value of the gap between the mask and the substrate surfaces. By comparing the gap value on different positions of the mask, we are able to align the mask and the substrate to a high degree of parallelism which stabilizes the gap distance. Moreover, with the use of ISPI technique and dynamic feedback, we can precisely track in real-time the gap distance during the nanolithography process and maintain it with a nanometer level precision. The effect of the gap distance and scanning speed on lithography results is discussed, in order to find out optimal operating parameters which can both avoid friction between surfaces and also obtain narrowest lithography line-width. We demonstrate parallel lithography results with the use of a 5x5 array of bowtie aperture antennas as focusing elements, which produce feature line-width below 90 nm.

8819-4, Session 1

Detection limits for nanoparticles in solution with classical turbidity spectra

Gilles Le Blevennec, Théo Chevallier, Commissariat à l'Énergie Atomique (France)

Detection of nanoparticles in solution is required to manage safety and environmental risks. Spectral transmission turbidity method has now been known for a long time. It is derived from the Mie Theory and can be applied to any number of spheres, randomly distributed and separated by large distance compared to wavelength. Here, we describe a method for the determination of size, distribution and concentration of nanoparticles in solution using UV-Vis transmission measurements. The method combines Mie and Beer Lambert computation integrated in a best fit approximation. In a first step, a validation of the approach is completed on silver nanoparticles solution. Validation of results is done with Transmission Electronic Microscopy measurements for the size distribution and an Inductively Coupled Plasma Mass Spectrometry for the concentration. In view of the good agreement obtained, a second step of work focuses on how to manage the concentration to be the most accurate on the size distribution. Those efficient conditions are determined by simple computation. As we are dealing with nanoparticles, one of the key points is to know what the size limits reachable are with that kind of approach based on classical electromagnetism. Taking into account the transmission spectrometer accuracy limit we determine for several types of materials (metals, dielectrics, semiconductors) the particle size limit detectable by such a turbidity method. These surprising results are situated at the quantum physics frontier.

8819-5, Session 1

Graphene metrology: investigating CVD-graphene microstructure changes with growth pressure using fluorescence quenching microscopy

Hamed Hosseini Bay, Paige Romero, Zafer Mutlu, Isaac Ruiz, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

The exceptional structure and properties of graphene made it an interesting and remarkable topic for research in recent years. Many applications including flexible electrodes for rechargeable batteries and supercapacitors, solar cells, electronic circuitry, sensing platforms and drug delivery have been foreseen for graphene and graphene-based sheets. Accordingly, chemical vapor deposition (CVD) is believed to be the most promising method for industrial-scale synthesis of graphene. In the past few years, a method based on fluorescence quenching of fluorescent dyes by graphene have been developed by our group as a high-throughput non-invasive quality control method for metrology of CVD-graphene sheets. In this method, a thin layer of fluorescent dye is applied on graphene and the energy transfer from dye molecules to graphene makes it possible to observe graphene sheets on arbitrary substrates. There are several parameters in a CVD system, which define the microstructure of graphene, chief among which is the growth pressure. Herein, we investigate the changes of graphene microstructure in different pressures implementing this method. Our results suggest that at lower pressures, graphene growth domains (grains) are significantly larger but there would be more defects in the subsequent graphene sheets. Moreover, results indicate that Fluorescence quenching microscopy (FQM) yields more insight about the dramatic change of the microstructure and quality of the sheets compared to scanning electron microscopy (SEM) and atomic force microscopy (AFM). Furthermore, Nucleation and growth of the graphene layers have been investigated as well.

8819-6, Session 2

New generation CMOS camera for semiconductor defect inspection applications *(Invited Paper)*

Wei Zhou, Darcy Hart, Rudolph Technologies, Inc. (United States)

Semiconductor defect inspection industry is always driven by defect detection rate and through-put. With semiconductor fabrication technology node advances to 2X ~1Xnm range, wafer processing critical macro defect size reduces to a few microns, approaching to typical silicon area scan camera pixel size range. Higher resolution image utilizes more detector pixels to represent the 2D defect, corresponding to smaller field of view on wafer, which fundamentally limits inspection throughput. Instead of recognizing defect shape, most of time detecting the existence of defect is more critical for high throughput volume production; therefore single pixel defect detection becomes more and more essential, which is fundamentally constrained by camera performance.

There are a numerous CMOS detectors based on different generation of CMOS technologies. Unfortunately, most of the time the vendor's data sheet cannot be easily converted into camera performance description for the end user due to different emphasis. This paper presents a model to describe camera performance for semiconductor machine vision. Most of performance items descried in camera industrial general protocols like EMVA1288 are condensed into two complex charts: dynamic range and noise profile, which address all critical factors for low defect contrast high speed semiconductor machine vision applications.

Current mainline cameras and high-end OEM cameras are evaluated with this model. Camera performances are clearly differentiated among CMOS technology generations and integration vendors, which will facilitate application-driven camera selection and operation optimization. The new challenges for CMOS detectors are discussed for semiconductor inspection applications.

8819-7, Session 2

Novel LED coupling design for semiconductor inspection illumination and application extensions *(Invited Paper)*

Wei Zhou, Rudolph Technologies, Inc. (United States)

High speed strobe based illumination scheme is one of the most critical factors for high throughput semiconductor defect inspection applications. HB LEDs are always the first and best option for such applications due to excellent flash-to-flash spatial and temporal stability, fast responding time, larger linear intensity range and no heat issue for - extremely low duty cycle applications. For some applications where a large area is required to be illuminated simultaneously, it remains a great challenge to efficiently package a large amount of HB-LEDs in a highly confined 3D space, to generate a seamless illuminated area with high luminance efficiency and spatial uniformity.

Traditional circular shaped TIR lens can be optimized for better luminance control, but inherently introduce spatial non-uniformity due to air gaps between lens channels. A novel 3D structured TIR lens is presented in this paper. The non-circular edge shape fundamentally reduces the intensity drop at the channel boundaries, while positive curvatures on the TIR lens's top surface efficiently guide the light into desired angular space. Number of edges and radius of top surface curvature are control parameters for system level performance and manufacture cost trade-off. With the novel advantages, the proposed 3D structured TIR lens also maintains the benefits of traditional TIR lens such as coupling efficiency and mold manufacture capability.

The applications can be extended into other non-illumination area like parallelism measurement and solar panel efficiency enhancement.

8819-8, Session 2

6-DOF displacement and angle measurements using heterodyne laser encoder

Ssu-Wen Pan, Hung-Lin Hsieh, National Taiwan Univ. of Science and Technology (Taiwan)

A novel heterodyne laser encoder for 6-DOF displacement and angle measurements is proposed. The system configuration is simple and easy to perform. It combines the advantages of heterodyne interferometry, grating shearing interferometry, and Michelson interferometry.

A heterodyne light beam is generated by using an Electro-Optic modulating technique for amplitude modulation. When the expanded heterodyne beam with four orthogonally polarized beams is focused on a two-dimensional semi-transmission grating, two detection configurations for in-plane (x and y directions) and out-of-plane (z direction) will be obtained. The zeroth and first order diffraction beams of x and y axes partially overlap and interfere with each other. By means of measuring the phase variations of the interfering signals from the moving grating, the grating movement in x and y directions can be acquired. Besides, the grating movement in z direction can be obtained by detecting the optical-path difference between the reference beam and the reflection beam from the semi-transmission grating. Furthermore, by using the beam dividing method, the angle information (θx, θY, θZ) can be measured without changing the original optical configuration.

Feasibility and performances of the proposed laser encoder have been addressed and demonstrated by using displacement and angle measurement experiments. The experimental results show that our proposed method has the ability to measure 6-DOF displacements and angles information with high system stability. The measurement resolutions of displacement and angle are about 2 nm and 0.01. Comparing with other commercial measurement instructions, this laser encoder has the advantages of high resolution, high repeatability, and high flexibility.

8819-9, Session 3

Nanomanufacturing concerns about measurements made in the SEM I: imaging and its measurement *(Invited Paper)*

Michael T. Postek, András E. Vladár, National Institute of Standards and Technology (United States)

The high resolution of the SEM is especially useful for qualitative and quantitative applications for both nanotechnology and nanomanufacturing. But, should users be concerned about the imaging and measurements made with this instrument? Perhaps one should or, at a minimum, understand some of the uncertainties associated with those measurements. It is likely that one of the first questions asked when the first scanning electron micrograph was ever taken was: "...how big is that?" The quality of that answer has improved a great deal over the past few years, especially since SEMs are being used as a primary tool on semiconductor processing lines to monitor the manufacturing processes. These needs prompted a rapid evolution of the instrument and its capabilities. Over the past 20 years or so, instrument manufacturers, through this substantial semiconductor industry investment of research and development (R&D) money, have vastly improved the performance of these instruments. All users have benefitted from this investment, especially where metrology with an SEM is concerned. But, how good are these data? This presentation will discuss a sub-set of the most important aspects and larger issues associated with imaging and metrology with the SEM. Every user should know, and understand these issues before any critical quantitative work is attempted.

8819-11, Session 3

Stability requirements for repeatable scanning probe nano-metrology *(Invited Paper)*

Ndubuisi G. Orji, Ronald G. Dixson, National Institute of Standards and Technology (United States)

The requirements necessary to obtain stable and repeatable scanning probe dimensional measurements are continually becoming more stringent. This is due to the needs of industries such as semiconductor lithography (patterned features) and chemicals (nanoparticles) where the measurands could be less than 10 nm in size. In addition to the challenging dimensions being measured, the uncertainty requirements are even smaller.

When designing highly repeatable and traceable scanning probe microscopes, it is essential to consider environmental requirements such as temperature and vibration, in addition to following accepted precision engineering principles such as symmetric design, separation of metrology and force loops, and elastic averaging. The environmental factors determine if a well-designed instrument can achieve stable and repeatable results. We present work and results on temperature, vibration, and acoustic requirements for a stable and highly repeatable atomic force microscope. The test case for our work has a temperature stability of below 5 mK over 48 hours, and a vibration reading of below 0.025 micrometers per second for $1 \leq f \leq 200$ Hz (integrated over one third octave). We also look at some of the key requirements needed to obtain repeatable probe based dimensional measurements in ambient environments.

8819-12, Session 3

Advance in dimensional measurements of nano-objects based on defocusing of the electron probe of a scanning electron microscope

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Measurement of geometrical parameters of nano-objects with the help of a scanning electron microscope (SEM) is based on analysis of video-signal curves obtained when the SEM operates in the low-energy secondary electron imaging mode. The SEM video-signal curve represents a convolution of the actual profile of the nano-object and the instrumental function which depends on many parameters including the electron probe diameter. The electron probe diameter can be relatively easily varied during the experiment by means of defocusing of the electron probe. In the present paper, we study the dependence of the profile of the video-signal curves versus the electron probe diameter for various types of nano-objects including spherical nanoparticles, protrusions located on a flat surface, etc. We found out that the distance between certain points located on the video signal curve is a linear function of the diameter of the electron probe. Using such linear dependence in the limiting case when the probe diameter goes to zero, one can deduce the actual size of the nano-object.

8819-18, Session 3

NSF nanomanufacturing program and its implications for measurement and control *(Invited Paper)*

Khershed P. Cooper, National Science Foundation (United States)

The NSF Nanomanufacturing Program supports fundamental research in novel methods and techniques for batch and continuous processes, and top-down and bottom-up processes leading to the formation of complex nanostructures, nanodevices and nanosystems. The program leverages advances in the understanding of nano-scale phenomena and processes, nanomaterials discovery, novel nanostructure architectures, innovative nanodevice and nanosystem design. It seeks to address issues such as quality, efficiency, scalability, reliability, safety and affordability. The program encourages research in the development of new nano-scale processes and production systems based on computation, modeling and simulation and use of process sensing, monitoring, and control. Research in instrumentation and metrology is an integral part of the program. Additionally, the program supports education of the next generation of researchers, and encourages building a workforce trained in nanomanufacturing systems. It is also interested in understanding long-term societal implications of large-scale production and use of nano-scale materials. For this, it encourages the development of standards. This paper will describe the program philosophy.

8819-10, Session 4

Nanomanufacturing concerns about measurements made in the SEM II: specimen contamination

Michael T. Postek, András E. Vladár, Purushotham P. Kavuri, National Institute of Standards and Technology (United States)

The scanning electron microscope (SEM) has gone through a tremendous evolution to become a critical tool for many and diverse scientific and industrial applications. The improvements that have been made have significantly improved the overall SEM performance and have made

the instrument far easier to operate. But, ease of operation also fosters operator complacency. In addition, the user friendliness has reduced the "apparent" need for more thorough operator training for using of these instruments. Therefore, this overall attitude has fostered the concept that the SEM is just another expensive digital camera or another peripheral device for a computer. Hence, a person using the instrument may be lulled into thinking that all of the potential pitfalls have been eliminated and they believe everything they see on the micrograph is always correct. But, this may not be the case. The first paper in this series, discussed some of the issues related to signal generation in the SEM, instrument calibration, electron beam interactions and the need for physics-based modelling to accurately understand the actual image formation mechanisms. All these were summed together in a discussion of how these issues effect measurements made with the instrument. This second paper, discusses another major issue confronting the microscopist: specimen contamination. Over the years, NIST has done a great deal of research into the issue of sample contamination and its removal and elimination and some of this work is reviewed and discussed here.

8819-13, Session 4

Quantitative microscope characterization for sub-nm parametric uncertainties of sub-10 nm CD arrays *(Invited Paper)*

Bryan M. Barnes, Jing Qin, Martin Y. Sohn, Hui Zhou, Richard M. Silver, National Institute of Standards and Technology (United States)

We have recently reported [1] the parametric fitting, with uncertainties, of 30-line and 100-line arrays with sub-20 nm nominal critical dimensions. Although these arrays have a 60 nm nominal pitch and are measured using 450 nm light, the arrays do not fill the field of view and a continuum of high-frequency content is present in the measured images. The inherent difficulty in accurate measurement of such finite arrays is the characterization of the optical platform. Each scattered angle traverses the collection path differently, which confounds direct simulation-to-experiment fitting. In addition, the intensity at each angle of incidence may also vary, requiring characterization of the illumination path.

To enable these parametric measurements, the transmissivity of the illumination and collection paths must be known as functions of polarization and angle. The collection path tool function must be applied to each scattering order from the simulation in the Fourier domain. Upon recombination of these orders, a more faithful reproduction of the image is achieved and rigorous, quantitative fits are then performed. Techniques for tool characterization will be presented for visible and deep-ultraviolet microscopes with practical examples based on measurements of several targets.

[1] R.M .Silver, et al., "Sub-nanometer parametric uncertainties using through-focus and angle-resolved optical metrology," SPIE Advanced Lithography 2013.

8819-14, Session 4

Pulse-to-pulse stability analysis in a frequency-doubled, q-switched Nd:YAG rod-laser

Matheus A. Tunes, Brazilian Navy (Brazil); Cláudio Geraldo Schön, Escola Politecnica da Univ. de São Paulo (Brazil); Niklaus U. Wetter, Instituto de Pesquisas Energéticas e Nucleares (Brazil)

The Nd:YAG Laser, Q-switched and side-pumped by diode lasers, is widely studied in the scientific area since it is an excellent source of short and high-energy pulses that are attractive to many physical applications like LIBS and LIDAR systems, medical surgery, industrial applications like cutting, drilling and many others.

Although this Laser system is used in many applications because of its efficiency, small size and low cost, the experimental setup has many difficulties regarding pulse-to-pulse stability. Specifically when passively Q-switched and wavelength-doubled to 532 nm, using a non-linear crystal for second harmonic generation (KTP), this instability may greatly hamper the application of the resonator. The main reason for this amplitude jitter is the non-linear birefringence of YAG and the fact that plane-plane resonators are normally used in conjunction with high-power solid-state lasers.

A widely accepted scientific analysis of this pulse-to-pulse instability is the monitoring of the output power as a function of time in a y-t diagram, that goes either over a series of pulses or, in other cases, takes a couple of hours [1-3].

Our work shows a fast and efficient comparative methodology to estimate the degree of power stability of a Laser resonator operating in the Q-switched regime observing statistical fluctuations of the pulse area. Additionally we perform a Monte-Carlo simulation in the solution of the Q-switching rate equations that reproduces the experimental data in some aspects.

To confirm the validity of our method, we performed a characterization of a plane-parallel Nd:YAG Laser operating at 532 nm. This characterization was conducted in two parts: first without a polarization-stabilizing, quarter-wave plate, and then, with the plate. As optimization mechanism, the quarter-wave plate is a widely explored issue in scientific papers [4]. The standard deviation of the pulse area histogram with the quarter-wave plate exhibits and order of magnitude smaller jitter and this fact can be used as a stability criterion in pulsed Laser systems.

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[4] W. C. Scott and M. de Wit. Applied Physics Letters 18(1) (1971) 3-4;

8819-15, Session 4

Piezoelectricity and its effect monitoring seismicity

Umesh P. Verma, BIT Sindri (India); Amitabh Sharma, M.J.K. Girls Inter College (India)

Piezoelectricity for the first time defined by Madam Curie (1880 in UK) and explained in detail by Jacuous curie in France was the generation of electricity and voltage due applied by mechanical stress on the piezoelectric material like quartz, tourmaline, zirconium, benitoite, lead, belemnite like ceramic material are sensitive to mechanical stress which are responding the stress and strain in form of generated voltage. Voltage direction depends on the polarization of the crystal and actuation stress .At temperature below Curie point, however, each crystal has tetrahedral or rhombohedra symmetric and dipole moment. The domain in the ceramic element is aligned by exposing the element to a strong direct current or electric power. the electromechanical coupling factor K and indicator of the effectiveness with which a piezoelectric material converts mechanical energy electrical energy depends on mode of vibration, shape of the ceramic material etc. Stress may be in nature geothermal energy {mantle's convective current (kogeanou2007)}, hydrostatic pressure, directed pressure in the incumbent rock (M.P.Billings), A. Holmes (1962) ,tectonic moment stored in the form of strain in the epicentres' zone of fault blocks.

Voltage or current generated corresponds to the in surged stress by the equation:

E=-(g33T) ---------------- (1) and Q=-(d33F) --------------------- (2)

Where, E=electric field,g33=piezoelectric voltage constant=stress on ceramic charge, Q=generated charge=applied force,d33=piezoelectric charge constant.

The stress strain relationship are in corporatized in dealing with the amount of voltage and direction of current generation in the piezoelectric substances that subject to predictable rupture in amount &direction and in approximation. Circuit and block diagram devised by the author in the paper explains inthe Principle and Mechanism section for decvice to be used for sensing the stress in terms of piezoelectricity developed due to impending seismic stress on situ.

8819-16, Session PWed

Study of ion beam damage in magnetic tunnel junction on FIB prepared samples

Kwangho Park, SAMSUNG Electronics Co., Ltd. (Korea, Republic of); Cheolwoong Yang, Sungkyunkwan Univ. (Korea, Republic of); Dongwoo Nam, Kyuman Hwang, Junsoo Bae, Juhyeon Ahn, Jin Choi, Samsung Electronics Co., Ltd. (Korea, Republic of); Sangsup Jeong, Hanku Cho, Samsung Electronics Co., Ltd. (Korea, Republic of)

Magnetic Random Access Memory (MRAM) has emerged as the leading candidate for future universal memory due to its non-volatility, excellent endurance and read/write performance [1]. The magnetic tunnel junction (MTJ) is a data storage element in MRAM and is basically composed of two ferromagnetic layers separated by the magnesium oxide (MgO) tunnel barrier. MgO between two ferromagnetic layers was adopted to enlarge the resistance difference between two kinds of magnetic arrangements by tunneling current through MgO. Like this, it is important to understand Characterization of MgO for developing Mram. Due to thin thickness of MgO, FIB milling should be used for the preparation of TEM specimens in Mram. The major problem in MgO sampling by FIB milling is the transform of MgO between two ferromagnetic due to FIB induced damage, which leads to high tunnel current through MgO and high resistance difference between two kinds of magnetic arrangements. An understanding of FIB generated artifact on MgO is important to analysis Mram and to optimize the sample preparation process. The normal ion beam damage are compared with low-kV FIB ion beam damage on blanket MgO wafer. Experiments were performed using Helios 450 FIB(FEI) and XV-200TBs(SII) with gallium ion sources operated at 30kV to 1kV, respectively. As a preliminary, the thicknesses of all specimens were fixed at 100nm for the final ion beam milling currents of 210pA(30kV) by Helios 450 FIB(FEI). Specimens of 100nm were transferred to low-kV FIB (Helios 450/XV-200TBs) to do the low-kV ion milling. Now each specimen has a 2kV cleaned surface and a 30kV FIB prepared surface. In this paper, we understand the normal ion beam damage on blanket MgO through changing beam current and beam voltage. Then we present the optimized recipe and which equipment is better to analysis

8819-17, Session PWed

Development of standard operating protocol for the nanoparticle size measurement and analysis by using a scanning electron microscopy

Hyuksang Kwon, Eun Ji Noh, Soo Jin Kim, Nam Woong Song, Korea Research Institute of Standards and Science (Korea, Republic of)

The multi-functional nanoparticles are promising for various applications such as biocompatible nanobio sensors and nanomedicines for diagnostics. However, the potential hazardous effects of the nanoparticles on the living bodies have been reported to be dependent on their size in some articles. It is prerequisite to provide an accurate size measurement technique for the correlation of toxicity and the size of nanoparticles as well as to prepare the size selected nanoparticles with narrow distribution. Since a scanning electron microscopy (SEM) is an easily accessible method to characterize nanostructures, we developed a standard operating protocol for the nanoparticle size measurement and analysis by using an SEM.

SEM images of more than 100 nanoparticles were analyzed using the image J 1.45s software. Smaller sizes of nanoparticles appeared with the increase of the accelerating voltage and the decrease of the filament current. The signal to noise ratio of image analysis and the image resolution were also observed with varying the accelerating voltage and the filament current. Then the size change with repeated e-beam irradiations was observed. It was noted that the e-beam irradiation for 1 min, comparable with the time required for the best alignment, makes the size increase of ca. 1 ~ 2 nm compared with the pre-irradiation condition. It means that the alignment time before the image acquisition should be minimized as short as possible under the mild imaging condition. Now, we are developing the standard operating protocols for the SEM measurement with a certified reference material to secure the traceability chain.

8820-1, Session 1

Fabrication of ambipolar gate-all-around field-effect transistors using silicon nanobridge arrays

Jin Yong Oh, M. Saif Islam, Univ. of California, Davis (United States)

In this work, we present simple methods for creating silicon nanobridge (NB) arrays with repeatability and demonstrate the fabrication of gate-all-around field-effect transistors (GAA-FETs) using NB arrays. P-type NBs of a low doping concentration were synthesized using SiH4, B2H6, HCl gases via the VLS technique directly on the arrays of silicon electrode-pairs. By depositing citrated gold colloids (diameter 200 nm, 7.0x10^8 / cm^3) with 7 % hydrofluoric (HF) acid for 2 min, NB arrays were achieved with a yield of up to 97 %. Subsequently, GAA-FETs were fabricated based on NB arrays. Regardless of the number of NB channels, GAA-FETs exhibited ambipolar transfer-characteristics that are typically observed in Schottky barrier FETs. Although effectively suppressed by a surround gate for a low drain bias of -50 mV, drain leakage current substantially increased from 0.1 pA to to 20 nA as a drain bias increases from -50 mV to -2 V. The significant increase of leakage current is attributable to reduction of the Schottky barrier width by the increase of drain bias. The unexpected ambipolar behaviors of our GAA-FETs suggest that gold impurities presumably cause Schottky barriers at the interface between NBs and silicon electrodes.

8820-2, Session 1

Nanostructured metal-insulator-semiconductor (MIS) devices for photoelectrochemical applications *(Invited Paper)*

Daniel V. Esposito, Thomas P. Moffat, National Institute of Standards and Technology (United States); A. Alec Talin, Sandia National Labs., California (United States)

Using photoelectrochemical cells (PECs) to produce H2 from the electrolysis of water is a promising approach to harvest solar energy. However, the performance of PEC devices is often limited by low conversion efficiencies or poor stability of semiconducting photoelectrodes. In order to overcome these issues, we have explored a metal-insulator-semiconductor (MIS) photoelectrode architecture that decouples the stability of a semiconductor from its ability to efficiently absorb visible light. The critical component of the MIS design is a thin (1-3 nm) oxide layer that protects the photon-harvesting semiconductor from the corrosive electrolyte while facilitating tunneling of minority carriers between the semiconductor and metallic collector structures.

In this presentation, two nano-scale modifications to Si-based MIS devices are described that lead to substantial improvement in their performance. These include the implementation of high-quality, thermally-grown oxide layers and bilayer metallic collectors. These two modifications have enabled greatly improved photoelectrode performance through control of interfacial properties and engineering of the MIS barrier heights. Central to these studies are the use of in-situ, micro-scale scanning probe techniques (scanning photocurrent microscopy and scanning electrochemical microscopy) that allow for simultaneous evaluation of optical, electronic, and catalytic properties. It is shown that knowledge gained from these techniques can be invaluable in elucidating observations made from macro-scale measurements. In the final portion of this talk, efforts to achieve further improvement in MIS photoelectrode operation through the use of 3D MIS structures will be presented.

8820-3, Session 1

Electronic effects of defects in one-dimensional channels *(Invited Paper)*

Elliot J. Fuller, Deng Pan, Brad L. Corso, O. Tolga Gul, Philip G. Collins, Univ. of California, Irvine (United States)

As electronic devices squeeze down to the one-dimensional limit, unusual device physics can result, even at room temperature. Nanoscale conductors like single-walled carbon nanotubes (SWNTs) are particularly useful tools for experimentally investigating these effects. This talk will focus on our characterization of point defects in SWNTs and their electronic consequences. A single scattering site in an otherwise ballistic SWNT can dominate two-terminal device characteristics [1] and provide the amplification to observe single electron events at room temperature. Defect contributions have been investigated using scanning probe methods [2] and exploited in single-molecule sensing experiments [3].

1. B. Goldsmith, et. al., Science 315, 77 (2007).

2. S.R. Hunt, et. al., Nano Letters 11, 1055 (2011). S.R. Hunt, et. al., Phys. Rev. B 85, 235418 (2012).

3. B. Goldsmith, et al., Nano Letters 8, 189-94 (2008). Y. Choi, et. al., Science 335, 319 (2012). Y. Choi, et. al., JACS 134, 2032 (2012).

8820-4, Session 2

Role of materials, geometry, and process conditions in tantalum oxide memristor performance *(Invited Paper)*

Andrew J. Lohn, Patrick R. Mickel, James E. Stevens, Michael T. Brumbach, Matthew Marinella, Sandia National Labs. (United States)

Memristors, also referred to as resistive memory or ReRAM, are nanoscale circuit elements that are gaining widespread interest as possible Flash or DRAM replacements and also as passive non-linear circuit elements in analog applications such as neural networks. These two-terminal devices are able to change their resistance such that binary, multi-level cell, or analog values can be stored. In tantalum oxide based memristors, which have shown excellent performance in terms of speed, endurance and power consumption and which are currently being developed by several memory manufacturers as Flash replacement, the internal structure of the device and switching mechanism are not well understood. At Sandia, we have fabricated a large number of tantalum oxide based devices by systematically varying a wide range of parameters including electrode materials, stoichiometry, deposition system and post-growth temperatures. Extensive characterization of the subsequent materials and devices has revealed structure that we have correlated to specific performance parameters. The correlation between material properties and device performance has shed light on the impact of geometry on TaOx memristors and guided us toward a clearer understanding of their operating mechanisms. With these insights we explain the origin of the desirable features exhibited in our devices and provide a path forward toward developing devices with unique and sought-after traits.

8820-5, Session 2

ZnO Power transistors for household appliances *(Invited Paper)*

Gary S. Tompa, Nick M. Sbrockey, Structured Materials Industries, Inc. (United States)

No abstract available

8820-6, Session 2

Development of dual-gated bilayer graphene device structures *(Invited Paper)*

Stephen W. Howell, Thomas E. Beechem III, Taisuke Ohta, Khalid M. Hattar, Allister B. Hamilton, Sandia National Labs. (United States)

We will present our efforts to fabricate chip-scale Bernal-stacked bilayer graphene (BLG) device structures using an epitaxial growth process with a semi-insulating 6H-SiC substrate. Bernal stacked bilayer graphene has a bandstructure that can be modified via the application of a transverse electric field. Importantly, this field creates a bandgap having a magnitude commensurate with the field thereby providing a pathway to tunable electronics. This is unique to Bernal bilayer and is not found in monolayer graphene. To leverage this bandgap, a dual-gated (top and bottom gates) structure is needed not only to create the bandgap but also to place the Fermi level within it. Realizing such a dual-gated structure is, however, complicated in epitaxial-BLG on SiC, since there is not an appreciable oxide for the back-gate dielectric as is the case when graphene rests on silicon. Furthermore, to take full advantage of BLG's unique properties for electronic and optical applications, synthesis and fabrication techniques must be developed to produce gated BLG device structures over a large area with sufficient yield. In response, we will present methods that demonstrate: 1) chip-scale BLG synthesis on SiC(0001), 2) creation of a back-gate using ion implantation, 3) synthesis of quasi-free standing BLG on SiC(0001) after implantation, and 4) bandgap control using a dual gated structure.

Recently, we have successfully demonstrated chip-scale BLG synthesis on SiC that was of reasonable electronic quality. The as grown graphene was Bernal stacked with a mobility of 2,600-4,000 cm2/Vs (verified by low temperature magneto transport measurements and Raman Spectroscopy/Lee et al. Nanoletters (11) 3624 2011). Ion implantation of nitrogen was then utilized to create a conductive backplane buried in the SiC as verified by capacitance and current leakage measurements. We successfully synthesized quasi-freestanding BLG on SiC(0001) after implantation. The quality of this graphene film was verified using Raman spectroscopy. Finally, we have successfully fabricated back-gated BLG FETs, where the implant serves as the back-gate.

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8820-7, Session 3

Nanowire LEDs and solar cells *(Invited Paper)*

Silvija Gradecak, Massachusetts Institute of Technology (United States)

No abstract available

8820-8, Session 3

Controlled lasing in GaN nanowires *(Invited Paper)*

Qiming Li, Huiwen Xu, Jeremy B. Wright, George T. Wang, Igal Brener, Ting-Shan Luk, Weng W. Chow, Jeffrey J. Figiel, Karen Cross, Sandia National Labs. (United States)

No abstract available

8820-9, Session 3

Nanowires for next generation photovoltaics *(Invited Paper)*

Ray R. LaPierre, McMaster Univ. (Canada)

No abstract available

8820-10, Session 3

Broadband, fast, and polarization-sensitive photodetector based on dense, macroscopically-long, optically-thick, and aligned carbon nanotubes *(Invited Paper)*

Sebastien Nanot, Rice Univ. (United States); Aron W. Cummings, Sandia National Labs., California (United States); Cary L. Pint, Vanderbilt Univ. (United States); Akira Ikeuchi, Takafumi Akiho, Kazuhisa Sueoka, Hokkaido Univ. (Japan); Robert Hauge, Junichiro Kono, Rice Univ. (United States); Francois Leonard, Sandia National Labs., California (United States)

No abstract available

8820-11, Session 3

Polycrystalline nanowire photonics *(Invited Paper)*

Reginald M. Penner, Univ. of California, Irvine (United States)

Nanocrystalline nanowires of composed of CdSe and CdTe have been prepared using the Lithographically Patterned Nanowire Electrodeposition (LPNE) process. In this talk, we describe the high throughput synthesis of lithographically patterned arrays of ultra-long nanowires that are ideally suited to the fabrication of photonic devices, and we disclose the properties of arrays of these nanowires for detecting light and for generating light.

8820-12, Session 4

Van der Waals nanoepitaxy: mechanism and applications *(Invited Paper)*

Xiuling Li, Parsian K. Mohseni, Univ. of Illinois at Urbana-Champaign (United States)

No abstract available

8820-13, Session 4

Silicene: a new two-dimensional material made of silicon *(Invited Paper)*

Yukiko Yamada-Takamura, Japan Advanced Institute of Science and Technology (Japan)

No abstract available

8820-14, Session 4

Growth kinetics of monolayer graphene on Pd(111) *(Invited Paper)*

Suneel Kodambaka, Univ. of California, Los Angeles (United States)

In this talk, we present in situ low energy electron microscopy (LEEM) observations and density functional theory (DFT) calculations focused on understanding the growth kinetics of monolayer graphene on single-crystalline Pd(111). In our experiments, carbon-containing Pd(111) samples were heated to temperatures around 900 oC and cooled to lower temperatures to promote surface segregation of carbon in the form of graphene. LEEM images and electron reflectivity data are acquired from the sample during graphene growth at a constant temperature as a function of incident electron energy and annealing time. We find that the area of graphene increases linearly with time. Interestingly, the work functions of graphene-free regions decrease (increase) during the growth (dissolution) of graphene. DFT calculations show that Pd work function can change due to the formation of metastable carbides and due to precipitation of C adatoms on the surface. Based upon our results, we suggest that attachment-limited kinetics govern the growth of graphene on Pd(111).

8820-15, Session 4

Deposition of aluminum titanium oxide layers with a graded refractive index: optically tunable encapsulation for optoelectronic devices

Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States); Richard E. Demaray, Antropy, Inc. (United States) and Demaray, LLC (United States); Kate J. Norris, Univ. of California, Santa Cruz (United States); Mark Johnson, Ravi B. Mullapudi, Tango Systems, Inc. (United States); Junce Zhang, Juan J. Diaz Leon, David M. Fryauf, Univ. of California, Santa Cruz (United States)

No abstract available

8820-16, Session 5

Development of amorphous silicon-gold growth templates for metal organic chemical vapor deposition of indium phosphide nanowire networks

Kate J. Norris, Junce Zhang, David M. Fryauf, Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States) and NECTAR (United States)

No abstract available

8820-17, Session 5

Growth and intentional doping of Si nanowires using Si-Cl-H growth chemistry *(Invited Paper)*

Joan M. Redwing, Sarah M. Eichfeld, Chito E. Kendrick, Haoting Shen, Meng-Wei Kuo, Theresa S. Mayer, The Pennsylvania State Univ. (United States)

The growth of silicon nanowires by the vapor-liquid-solid (VLS) method is of significant fundamental interest driven by practical applications in nanoelectronics, sensing and energy harvesting. The use of silicon tetrachloride (SiCl4) in combination with gold-catalyzed VLS has long been employed for the synthesis of Si whiskers and more recently for Si nano/microwire growth. The high temperatures (~1000oC) required for growth with SiCl4 combined with the Cl-based chemistry are advantageous for producing epitaxial Si wire arrays. Our studies have focused on investigating the mechanisms of Si nanowire growth with SiCl4 and the incorporation of intentional dopants. This work has revealed that the growth rate of Si nanowires with SiCl4 is controlled by gas phase chemistry and transport of reactant species to the growth surface under atmospheric pressure conditions. Si nanowires grown by VLS typically exhibit a <111> or <112> growth direction, however, Si nanowires with a <110> growth direction can be obtained with SiCl4 under conditions which promote stable {111} sidewall facets. Intentional boron doping of the Si nanowires using trimethylboron was also examined in order to investigate the mechanism of dopant incorporation in the wires. Multi-point resistance measurements carried out on single nanowires demonstrate uniform resistivity along the axial and radial directions of the nanowire. The results indicate that the primary route to dopant incorporation occurs via the liquid catalyst with negligible vapor-solid deposition and diffusion of dopants through the sidewalls of the nanowire.

8820-18, Session 5

III-V compound semiconductor nanowires *(Invited Paper)*

Chennupati Jagadish, The Australian National Univ. (Australia)

No abstract available

8820-19, Session 5

Dependence of hierarchical order of 1D-nanocrystals and heterostructures on the substrate surface properties: cubic versus hexagonal crystals *(Invited Paper)*

Babak Nikoobakht, National Institute of Standards and Technology (United States)

No abstract available

8820-20, Session 6

Plasma-enhanced atomic layer deposition of aluminum oxide coating for photo emission wavelength tuning of indium phosphide nanowires

David M. Fryauf, Univ. of California, Santa Cruz (United States) and NASA Ames Research Ctr. (United States); Andrew J. Lohn, Sandia National Labs. (United States); Byung Joon Choi, Steven J. Barcelo, Hewlett-Packard Labs. (United States); Kate J. Norris, Junce Zhang, Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States) and NASA Ames Research Ctr. (United States)

Semiconductor-oxide nanostructure (SON) devices can be a very intriguing material platform if optoelectronic properties of the original semiconductor nanostructures can be tuned by explicitly controlling properties of the oxide coating. This paper describes our finding that optical properties of semiconductor nanowires can be tuned

by depositing a thin layer of metal oxide. In this experiment, indium phosphide (InP) nanowires were grown by low-pressure metal organic chemical vapor deposition on silicon substrates with gold catalyst. InP nanowires formed three-dimensional nanowire networks from which collective optical properties were obtained. The InP nanowire network was coated with an aluminum oxide (AlOx) thin film deposited by plasma-enhanced atomic layer deposition (PEALD) using trimethylaluminum (TMA) as a metal precursor and oxygen (O2) as an oxidant gas activated by remote plasma. We focus on how several key optical characteristics of the InP nanowire network, such as peak wavelength of photoluminescence spectra, change as physical properties, for instance thickness, of the AlOx coating vary. We observed continuous blue shift in photoluminescence spectra when the thickness of the AlOx coating was increased. Possible causes for the blue shift include quantum confinement associated with the AlOx coating that contains fixed charges and confines photo generated electron-hole pairs within an area smaller than the Bohr radius in InP. Temperature dependence of PEALD AlOx coating density and carbon impurity level was also studied. Samples were further characterized by scanning electron microscopy, x-ray diffractometry, and energy dispersive x-ray spectroscopy in an attempt to explain the physical mechanisms for the blue shift.

8820-21, Session 6

Orientation, alignment, and polytype control in epitaxial growth of SiC nanowires for electronics application in harsh environments *(Invited Paper)*

Yaroslav Koshka, Rooban Venkatesh K. G. Thirumalai, Bharat K. Krishnan, Mississippi State Univ. (United States); Albert V. Davydov, National Institute of Standards and Technology (United States); J. Neil Merrett, Air Force Research Lab. (United States)

No abstract available

8820-22, Session 6

Size-controlled InAs quantum nanostructures in InP nanowire grown via the Au-free vapor-liquid-solid mode *(Invited Paper)*

Guoqiang Zhang, Danang Birowosuto, Nippon Telegraph and Telephone Corp. (Japan); Kouta Tateno, Hideki Gotoh, Tetsuomi Sogawa, NTT Basic Research Labs. (Japan)

We report on the first in-situ tuning of the InP/InAs hetero-nanowire (NW) diameter. The tuning ability enables us to freely engineer the size of the InAs segment in InP nanowire by varying the thickness and the diameter. Thus we could tune the bandgap in a wide range including the telecommunication window.

Semiconductor nanowires (NWs) have been expected as the next-generation build blocks in optoelectronics and electronics. The vapor-liquid-solid (VLS) mode has been widely used for the growth of the NWs due to its high controllability. The self-assisted VLS mode has been developed to avoid the incorporation of foreign catalyst materials like Au. InP NWs have been grown by the In-particle-assisted VLS mode. It has been found out that the In particle size at the tip could be increased or decreased during growth by modifying the III source flow rate [G. Zhang, et al: Appl. Phys. Exp. 5 (2012) 055201.]. This provides a new way to tune the NW diameter during the growth, a new controllable dimension in the NW synthesis.

The InP/InAs hetero-NWs were grown via the self-assisted vapor-liquid-solid (VLS) growth mode. We tuned the size of the In particle at the NW tip by modulating the In source flow rate, and then the NW diameter also changed during the growth. When the flow rate of TMIn is decreased, the In particle size decreases with growing because the supply of the In source becomes insufficient. This enables us to freely engineer the size of InAs segment in InP NW. Consequently, by studying the photoluminescence of the InAs segment in individual NWs at 4K, we could tune the bandgap in a wide range including the telecommunication window (1.3μm - 1.5μm).

8820-23, Session 7

Improvement in efficiency droop of GaN-based LEDs by optimization of active regions *(Invited Paper)*

Hao-Chung Kuo, Da-Wei Lin, Shih-Pang Chang, B. C. Lin, Chien-Chung Lin, Gou-Chung Chi, National Chiao Tung Univ. (Taiwan)

GaN-based light-emitting-diodes (LEDs) have been developed in various applications due to its widely tunable wavelength from ultraviolet to blue/green. Nevertheless, the most expected application, solid-state lighting, is still developing. Although the light-extraction efficiency has been significantly improved by different techniques, the internal quantum efficiency (IQE) still suffers a major obstacle. This efficiency droop behavior strongly limits the development of many specific applications which require the operation current of the InGaN/GaN LEDs under high injection levels.

Carrier overflow out of the active region as well as inefficient injection and transportation of holes have been identified to be the major reasons of efficiency droop. Conventional GaN-based c-plane quantum wells suffer from the quantum-confined Stark effect (QCSE) and electron overflow as a result of a spontaneous and piezoelectric polarization field parallel to the [0001] direction. On the other hand, the low hole mobility causes their feebleness in transportation along active region, such as insufficient transportation across the electron blocking layer (EBL) and accumulation of holes at the quantum wells near p-GaN.

In this paper, we first introduce the physical mechanisms of efficiency droop in GaN-based LEDs and its origin. Then we propose several methods to reduce this effect, such as alternative substrates, semi-polar (1-101) MQWs, low temperature insertion layer between n-GaN and MQWs, graded-thickness MQWs (GQWs), and graded-composition EBL (GEBLs). The results show that by reducing the polarization field in MQWS, enhancing hole transportation in MQWs, and enhancing hole injection across EBL, the efficiency droop behavior could be successfully reduced.

8820-24, Session 7

Nanoscale dopant distribution in nanowires: correlation with growth process and device properties *(Invited Paper)*

Lincoln J. Lauhon, Northwestern Univ. (United States)

No abstract available

8820-25, Session 7

Two step growth and fabrication of thermoelectric devices employing indium phosphide nanowire networks

Kate J. Norris, Junce Zhang, David M. Fryauf, Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States) and NECTAR (United States)

No abstract available

8820-26, Session 8

Guest adsorbate induced switching of electrical conduction in a metal-organic framework

A. Alec Talin, Sandia National Labs. (United States); Andrea Centrone, Paul M. Haney, National Institute of Standards and Technology (United States); Vitalie Savila, Michael E. Foster, Sandia National Labs., California (United States); Robert A. Kinney, Veronika A. Szalai, Heayoung Yoon, Dmitry Ruzmetov, National Institute of Standards and Technology (United States); Mark Allendorf, Sandia National Labs., California (United States)

Metal-organic frameworks (MOFs) are extended, crystalline compounds consisting of metal ions interconnected by organic ligands and characterized by permanent porosity that makes these materials highly attractive for gas storage, separations, and many other related applications. Electrically conducting or semiconducting MOFs would present a whole new class of electronic materials, with combined advantages of traditional inorganic semiconductors (crystallinity, relative thermal stability, and demonstrated epitaxial growth) with those of molecular electronics (low cost synthesis and control of electronic structure through chemistry). However, the largely ionic character of the ligand- to- metal center bonding and the lack of long-range delocalized orbitals render most MOFs electrical insulators. We describe a new approach wherein insertion of guest molecular specie (7,7,8,8-tetracyanoquinododimethane) that strongly interacts with the framework (Cu3BTC2) switches the MOF conductivity from insulating to Ohmic, while preserving its crystal structure. This method exploits the MOF structure as an active template and potentially allows conductivity to be tuned by modulating the MOF-guest's interactions with the MOF building blocks.

8820-27, Session 8

Ultrasensitive biomolecular assays with amplifying nanowire FET biosensors *(Invited Paper)*

Chi On Chui, Univ. of California, Los Angeles (United States)

In this talk, we will review our recent development and validation of the ultrasensitive electronic biomolecular assays enabled by our novel amplifying nanowire field-effect transistor (nwFET) biosensors. Our semiconductor nwFET biosensor platform technology performs low parasitics signal amplification in the electrical domain that requires neither labeling, enzymes, nor optics. We have designed and fabricated the biomolecular assay prototypes as well as the corresponding analytical procedures. We have also validated the assays' analytical performance in detecting key protein biomarkers in buffer and serum, and compared the results against the state-of-the-art nwFET bioassays.

8820-28, Session 8

Using tobacco mosaic virus template for the fabrication of three-dimensional hierarchical microbattery electrodes with high energy and high power density *(Invited Paper)*

Ekaterina Pomerantseva, Konstantinos Gerasopoulos, Markus Gnerlich, Philipp Odenwald, James Culver, Reza Ghodssi, Univ. of Maryland, College Park (United States)

We present a novel approach for the fabrication of lithium-ion microbattery electrodes which deliver high energy and high power density. The key enabling technology is the use of self-assembled Tobacco mosaic virus (TMV) nanoforests as a template for active battery materials. The self-assembling TMV is a genetically modified biological nanorod with increased chemical binding properties for enhanced manufacturability. High energy density is achieved due to the active surface area increase within a given footprint by combining TMV with three-dimensional (3D) microfabrication processes. The TMV nanostructure enables high power density through larger electrode/electrolyte contact area and faster charge transport.

The electrodes consist of an array of electroplated gold micropillars with an aspect ratio of three (60 µm high, 20 µm in diameter). The pillars are coated with the self-assembled nanoscale TMV template and subsequently metalized in-place. Active battery material (V2O5) is conformally deposited using atomic layer deposition (ALD) on the hierarchical micro/nano network. Electrochemical testing of these electrodes indicates a 3-fold increase in energy density, compared to the TMV-templated electrodes without micropillars, without increasing footprint area or reducing rate performance. Further increase in energy density can be achieved by increasing surface area of 3D microelements as demonstrated by fabrication and electrochemical testing of the electrodes with hollow gold micropillars. Scaling up energy density by increasing active material thickness beyond 100 nm revealed some loss in surface area which highlighted the importance of nanoscale engineering for achieving maximum energy and power density in energy storage systems.

8820-29, Session 9

Growth of epitaxial doped semiconductor and semimetallic plasmonic materials *(Invited Paper)*

Seth Bank, Erica M. Krivoy, Scott Maddox, The Univ. of Texas at Austin (United States)

No abstract available

8820-30, Session 9

Difference in formation of ferromagnetic MnAs nanoclusters on III-V semiconducting nanowire templates *(Invited Paper)*

Shinjiro Hara, Hiromu Fujimagari, Shinya Sakita, Masatoshi Yatago, Hokkaido Univ. (Japan)

Recent activities for semiconducting nanowires have gained much attention in the potential application to future electronic and photonic devices. However, there are less numbers of the reports of magneto nano-electronic, or spintronic, device applications, such as magnetic sensors and spin-polarized light-emitting diodes, utilizing vertical free-standing nanowires. The authors have realized many varieties of nanowires, e.g. GaAs, InP, and InAs nanowires, and GaAs/AlGaAs and GaAs/GaAsP core-shell ones, by catalyst-free selective-area metal-organic vapor phase epitaxy (SA-MOVPE) on partially SiO2-masked wafers of GaAs(111)B, Si(111), etc. We report here on the differences in ferromagnetic MnAs nanocluster formation on GaAs, GaAs/GaAsP, and InAs nanowire templates by SA-MOVPE, because there is not much information on dependence of the nanocluster formation on materials of the nanowire templates. GaAs and GaAs/GaAsP nanowires were grown at 750C, while InAs nanowires were grown at 580C. MnAs nanoclusters are formed commonly at six ridges between two {0-11} crystal facets on hexagonal prisms of III-V semiconducting nanowires presumably because many atomic steps exist between the crystal facets. Here, MnAs nanoclusters were grown "into" the nanowires, as a result of the phenomenon of endotaxy, because manganese source and hydrogen were supplied, i.e. no arsenic source supply. In the case of GaAs/GaAsP and InAs nanowires, however, MnAs nanoclusters were formed on the top {111}B surfaces of the nanowires, as well as at six ridges of the hexagonal prisms. The results obtained here possibly show that the

endotaxy of MnAs depends on the strength of atomic bonds in the host materials of nanowires.

8820-31, Session 9

Epitaxial growth of Si dots on AlN/Si (111) *(Invited Paper)*

Rod Beresford, Yana Cheng, Brown Univ. (United States)

No abstract available

8820-32, Session 9

Micro plasma enhanced chemical vapor deposition and etching of materials using atomic force microscope *(Invited Paper)*

Massood Tabib-Azar, National Science Foundation (United States)

No abstract available

8820-33, Session 10

Moisture barrier and chemical corrosion protection of silver-based telescope mirrors using aluminum oxide films by plasma-enhanced atomic layer deposition

David M. Fryauf, Univ. of California, Santa Cruz (United States) and NECTAR (United States); Andrew C. Phillips, Univ. of California (United States); Junce Zhang, Kate J. Norris, Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States) and NASA Ames Research Ctr. (United States)

An urgent demand remains in astronomy for high-reflectivity silver mirrors that can withstand years of exposure in observatory environments. The University of California Observatories Astronomical Coatings Lab has undertaken development of protected silver coatings suitable for telescope mirrors that maintain high reflectivity at wavelengths above 340 nm and into the mid-infrared spectrum. We present initial results of an experiment showing that plasma-enhanced atomic layer deposition (PEALD) can produce superior protective layers of transparent dielectrics.

Several novel coating recipes have been developed with ion-assisted electron beam deposition (IAEBD) of materials including yttrium fluoride, and oxides of yttrium, hafnium, titanium and tantalum. Samples of these mirror coatings were covered with conformal layers of aluminum oxide (AlOx) deposited by PEALD using trimethylaluminum as a metal precursor and oxygen as an oxidant gas activated by remote plasma. Samples of coating recipes with and without PEALD oxide undergo aggressive environmental testing, including high temperature/high humidity (HTHH), hydrogen sulfide (H2S) exposure, and abrasion/adhesion resistance. Samples were exposed to an environment of 80% humidity at 80°C for ten days in a simple test set-up, and tarnishing endurance was tested by exposure to H2S concentrations of 10-20 ppm for several days. H2S exposure and HTHH testing show visible results confirming that the PEALD oxide offers enhanced robust protection against chemical corrosion and moisture from an accelerated aging environment. Mirror samples are further characterized by reflectivity/absorption, ellipsometry, atomic force microscopy, and X-ray diffractometry before and after deposition of oxide coatings. AlOx is suitable for many applications and has been the initial material choice for this study. We are planning further experiment with other materials, particularly tantalum and titanium oxides, and silicon nitride.

8820-34, Session 10

Optical filters and antireflection coatings for high performance detectors *(Invited Paper)*

April D. Jewell, John Hennessy, Jet Propulsion Lab. (United States); Erika T. Hamden, Columbia Univ. (United States); Timothy M. Goodsall, Todd J. Jones, Alexander G. Carver, Michael E. Hoenk, Shouleh Nikzad, Jet Propulsion Lab. (United States)

Here we describe the development of optical coatings for silicon-based detectors for astronomy, planetary and terrestrial applications. At the Jet Propulsion Laboratory, thin-film optical filters are incorporated with existing detector technologies. We have used atomic layer deposition (ALD) to grow filters on silicon substrates. ALD is a technique whereby thin films are grown a monolayer at a time through a series of self-limiting chemical reactions at a substrate surface; thus, ALD offers nanometer-scale control over film thickness. We have characterized the nucleation and growth behavior of a variety of ALD films with materials characterization techniques such as spectroscopic ellipsometry and transmission electron microscopy as well as examined the interfacial chemistry of stacked layers. Based on this work we are able to achieve precision growth of multilayer films and provide tailored, repeatable performance targeted for specific applications. The behavior of these films matches that predicted by model-based designs of multilayer bandpass filters. A five layer film structure optimized to maximize transmission over a narrow band centered at 200 nm was deposited onto live CCDs. Quantum efficiency (QE) measurements match modeled film behavior remarkably well, showing improved performance at the target wavelength of 200 nm. Also under development are ALD coatings to enhance QE for a variety of spectral ranges. Broadband targets include 100-300 nm, 300-1000 nm, and 200-1000 nm; while narrower band benchmarks focus on improved QE for 100-200 nm, 200-235nm and 240-300 nm. The work described marks a significant advancement in detector technology and capability.

8820-35, Session 10

Surface modification of the PEALD Al2O3/GaSb interface for enhanced electrical performance *(Invited Paper)*

Erin R. Cleveland, Laura Ruppalt, Brian K. Bennett, Sharka M. Prokes, U.S. Naval Research Lab. (United States)

The integration of high-k dielectrics with high moblility III-V semiconductor materials is attracting widespread attention as an alternative to Si-based complementary-metal-oxide-semiconductor (CMOS) applications. Among the III-V's, GaSb is a promising as the channel material in high speed, low power metal-oxide-semiconductor-field-effect-transistors (MOSFETs) due to its high electron and hole mobilities, as well as a relatively narrow badgap. However, poor quality of the gate-oxide/GaSb interface has limited its use in microelectronics. A significant effort has been focused on surface preparations prior to ALD that removes the native oxide in order to ensure the best possible interface. Current approaches typically rely upon wet-chemical etches; however, this technique typically suffers from a lack of reproducibility, as well as potential contamination. Recently, we demonstrated the use of hydrogen plasma prior to plasma-enhanced-atomic-layer-deposition (PEALD) of Al2O3 on GaSb. Samples demonstrating good electrical characteristics correlated to elimination of Sb-oxide, decrease in elemental Sb, and increase in Ga2O3. Therefore, we compared the effectiveness of wet and dry surface treatments for improving the electrical properties of the PEALD Al2O3/GaSb interface. We evaluated the effectiveness of TMA as a standalone process to remove the native oxides from GaSb substrates that have undergone no additional wet chemical treatment and those dipped in HCl prior to TMA exposure. Furthermore, we investigated the use of hydrogen plasma prior to PEALD as a means to produce a suitable electrical interface. XPS and TEM were used to characterize composition and structure, while C-V measurements

were performed to evaluate the electrical integrity of the resulting surfaces.

8820-36, Session 10

Different intermixing regimes of metal-oxide and metal-sulfide multilayers synthesized by atomic layer deposition *(Invited Paper)*

Sergey V Baryshev, Argonne National Lab. (United States) and Euclid TechLabs, LLC (United States); Elijah Thimsen, Univ. of Minnesota (United States); Shannon C. Riha, Alex B. F. Martinson, Alexander V. Zinovev, Igor V. Veryovkin, Michael J. Pellin, Jeffrey W. Elam, Argonne National Lab. (United States)

Historically, the atomic layer deposition (ALD) community has focused intently on metal-oxides (MOs). It is known that multilayer MO films synthesized by ALD have morphology where discrete layers are separated by sharp boundaries within designated deposition regions – nanolaminate morphology. Solid-state diffusion at the deposition temperature is very low for these materials. The sharpness of interfaces in multilayer metal-sulfide (MS) thin films synthesized by ALD is virtually unexplored.

Comparison of MO nanolaminate MgO/ZnO and MS multilayer ZnS/SnS2/Cu2S, both synthesized by ALD, will be presented. Comparison is based on a newly proposed mixing number Mx, which is the diffusion distance of mobile atomic species during layer deposition divided by the layer thickness in which the mobile species is diffusing. Mx numbers were calculated from composition profiles measured by dual beam secondary ion mass spectrometry (SIMS) with ½ nm depth resolution. SIMS results confirmed that MO multilayer was in nanolaminate regime with Mx<<1, while MS multilayer was extensively premixed with Mx≈1 and >>1. This indicates that MS multilayer thin films are in an entirely different regime than MOs.

Since ultrathin multilayer ZnS/SnS2/Cu2S is of high interest due to its relevance for forming the photovoltaic alloy Cu2ZnSnS4 upon annealing, better understanding of solid-state transport in ALD could benefit for nanostructured photovoltaics/photocatalysis. Therefore, results of extended SIMS analysis will be reported. Most importantly, it was confirmed that mixing of the metal-sulfide binaries into Cu2ZnSnS4 obeys the predicted solid state reaction mechanism Cu2S+SnS2+ZnS 0Cu2SnS3+ZnS Cu2ZnSnS4 where the second step limits the overall reaction rate at low temperatures.

8820-37, Session 11

Study of Raman signal from indium phosphide nanowire networks coated with gold

Junce Zhang, David M. Fryauf, Univ. of California, Santa Cruz (United States) and NASA Ames Research Ctr. (United States); Kate J. Norris, Juan J. Diaz Leon, Univ. of California, Santa Cruz (United States) and NASA Ames Research Ctr (United States); Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States) and NASA Ames Research Ctr. (United States)

No abstract available

8820-38, Session 11

Single-polycrystalline core-shell silicon nanowires grown on copper

Kate J. Norris, Junce Zhang, David M. Fryauf, Univ. of California, Santa Cruz (United States) and NECTAR (United States); Elane Coleman, Gary S. Tompa, Structured Materials Industries, Inc. (United States); Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States) and NECTAR (United States)

The growth of silicon core-shell nanowires with a crystalline core and a polycrystalline shell on copper substrates pretreated with carbon via Plasma Enhanced Chemical Vapor Deposition (PECVD) was demonstrated. By altering the copper surface with carbon treatment and using gold colloids, highly dense silicon nanowire networks can be grown on copper substrates. Scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDX), x-ray diffraction (XRD), Raman spectroscopy, and transmission electron microscopy (TEM) were performed to characterize the nanowires. TEM showed that the core of the nanowires is single crystalline while the shell surrounding the single crystalline core is polycrystalline (single-polycrystalline core-shell nanowires). The nanowires have diameters ranging from 120 to 250nm including their crystalline cores which appeared to range from ~10-20nm. These crystalline cores appear to follow the length of the nanowires without expanding or narrowing. The diameter of the polycrystalline shell surrounding the core also remains consistent. Possible growth mechanisms that induce the spontaneous growth of single-polycrystalline core-shell silicon nanowires are discussed based on the structural analysis. There are several possible benefits obtained from this unique nanowire structure. For example, the single-polycrystalline core-shell nanowires with their large diameters allow for easier methods of electrical/thermal contact while maintaining the benefits of small diameter nanowires with their single-crystalline cores. The single-polycrystalline core-shell nanowires are assessed with the view toward a thermoelectric material with the concept that the small diameter single-crystal core could allow for efficient transport of charge carriers while the polycrystalline shell could effectively backscatter phonons.

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Conference 8821: High and Low Concentrator Systems for Solar Electric Applications VIII

Tuesday 27–27 August 2013

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8821-1, Session 1

A fiber luminescent solar concentrator with 5.7% optical conversion efficiency *(Invited Paper)*

Esmaeil-Hooman Banaei, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Univ. of Central Florida (United States); Ayman F. Abouraddy, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Conventional Luminescent Solar Concentrators (LSC's) are slab waveguides coated or doped with luminescence materials for absorption and guiding of light to the slab edges for conversion to electricity by attached PV cells. LSC's are a promising alternative for reducing the cost of solar power. Exploiting the advantages of optical fiber production, we present here a Fiber LSC (F-LSC) in which the waveguide is a polymer optical fiber. We propose a hybrid fiber structure for an efficient two-stage concentration of incident light into a small doped core and eventually to the fiber ends. Flexible sheets are assembled with fibers that can be bundled and attached to small-area PV cells. Fiber dimensions and directional guiding allow for geometrical gain improvement over that of existing LSC's. In addition, the undesired limit of LSC size is eliminated in one direction.

We present modeling and optimization of an F-LSC design using polarization ray tracing under realistic conditions with solar spectrum radiation and broad-band absorption and emission spectra with their inevitable self-absorption effect.

We also present the results of fabrication and optical characterization of such F-LSC using two off-the-shelf organic dyes and a commercially available polymer, COP. Fiber preforms, fabricated under optimized conditions for low light transport loss, are thermally drawn into sub-millimeter-size fibers. Characterization of several samples with various concentrations of the two dyes shows an optical conversion efficiency of 5.7% for a tandem combination of two fibers 2.5-cm long with the efficiency gradually decreasing to 3.1% with increase in fiber length to 10 cm.

8821-2, Session 1

Monte Carlo simulations of luminescent solar concentrators for building integrated photovoltaics

Shin Woei Leow, Carley Corrado, Melissa Osborn, Sue A. Carter, Univ. of California, Santa Cruz (United States)

Luminescent solar concentrators (LSCs) have the ability to receive light from a wide range of angles and concentrate the captured light on to small photo active areas. This enables LSCs to be integrated more extensively into buildings as windows and wall claddings on top of roof installations. LSCs with front facing PV cells collect both direct and concentrated light ensuring a gain factor greater than one. It also allows for flexibility in determining the placement and percentage coverage of PV cells when designing panels to balance reabsorption losses, power output and the level of concentration desired. A Monte-Carlo ray tracing program was developed to study the transport of photons and loss mechanisms in LSC panels and aid in design optimization. The program imports measured absorption/emission spectra and transmission coefficients as simulation parameters with interactions of photons in the panel determined by comparing calculated probabilities with random number generators. LSC panels with multiple dyes or layers can be simulated. Results of a thin single dye system optically coupled to a clear waveguide closely parallels measured data and reveals optimal panel dimensions and PV cell layouts for maximum power output.

8821-4, Session 1

Experimenal validation of ray-tracing/Monte-Carlo simulations for LSC-devices based on fluorophores with variable self-absorption

Zachar Krumer, Wilfried G. J. H. M. van Sark, Celso Mello Donegá, Ruud E. I. Schropp, Utrecht Univ. (Netherlands)

Luminescent solar concentrators (LSCs) are low cost photovoltaic devices, which reduce the amount of necessary semiconductor material per unit area of a photovoltaic solar energy converter by means of concentration. The device is comprised of a thin plastic plate in which luminescent species (fluorophores) have been incorporated. The fluorophores absorb the solar light and radia¬tively re-emit part of the energy. Total internal reflection traps most of the emitted light inside the plate and wave-guides it to a narrow side facet with a solar cell attached, where conversion into electricity occurs. The efficiency of such devices is as yet rather low, due to several loss mecha¬nisms, of which self-absorption is of high importance.

Combined ray-tracing and Monte-Carlo simulations is a widely used tool for efficiency estimations of LSC-devices prior to manufacturing. We have applied this method to a model experiment, in which we analysed the impact of self-absorption onto LSC-efficiency of fluorophores with different absorption/emission-spectral overlap, i.e., Stokes' shift.

We have also validated the model experiment and compared experimental with simulation results. We experimentally found that LSCs with type-II semiconductor nanocrystals as fluorophores are the least affected by self-absorption, while single compound semiconductor nanocrystals are affected the most. Simulations confirm this result. The suitability of the model for variable self-absorption effects has been assessed.

8821-5, Session 2

Holographic spectrum splitting in eight-junction, ultra-high efficiency photovoltaic module *(Invited Paper)*

Sunita Darbe, Matthew D. Escarra, Emily C. Warmann, Harry A. Atwater Jr., California Institute of Technology (United States)

To achieve photovoltaic solar energy conversion with greater than 50% module efficiency, the number of semiconductor junctions must be increased beyond the 3-5 used in conventional lattice-matched multi-junction photovoltaics. In this work, we demonstrate a photovoltaic module design that incorporates eight III-V semiconductor junctions arranged laterally as four dual-junction subcells operating electrically and optically in parallel. These eight bandgaps span the entire solar spectrum, and the corresponding alloys can be grown lattice-matched to GaAs and InP substrates. A compound holographic optical element splits the incoming solar spectrum into four spectral slices, each diffracted onto the appropriate tandem subcell. This compound element consists of a 4x3 array of volume holographic gratings, with grating parameters optimized using an algorithm based on generalized coupled wave analysis.

Concentration is shown to be essential to achieving 50% module efficiency with this geometry. Thus, a two-stage trough compound parabolic concentrator is incorporated into the design to achieve concentration of >100 suns. This concentration occurs after the spectrum is split to avoid negatively impacting the performance of the holographic optics. To accurately model the performance of this module, subcell performance is derated from detailed balance ideals by incorporating average external radiative efficiency of 0.3% and Jsc that is 90% of its ideal value. Additional realistic optical and electrical losses are included. A preliminary design achieves spectrum splitting with

75% optical efficiency, resulting in a two-terminal module efficiency of 35.1%. Considerable design space remains to be explored in this module geometry, with potential to reach 50% module efficiency.

8821-6, Session 2

Grating-over-lens CPV spectrum splitting systems with volume holographic optical elements

Juan M. Russo, Deming Zhang, The Univ. of Arizona (United States); Michael Gordon, College of Optical Sciences, The Univ. of Arizona (United States); Shelby D. Vorndran, Youchen Wu, Raymond K. Kostuk, The Univ. of Arizona (United States)

In previously described grating-over-lens spectrum splitting designs, a planar transmission grating is placed at the entrance of a plano-convex lens. A spectral range is diffracted at 15-30° from normal incidence and into the lens. The diffracted spectral range comes to a focus at an off-axis point and the undiffracted spectrum comes to a focus at the paraxial focal point. Since the diffracted wave is planar and off-axis, the off-axis focal points suffer from aberrations that increase the losses of the system. Field curvature, chromatic and spherical aberrations are compensated using defocusing and a curved focal plane (approximated with each photovoltaic receiver). Coma is corrected modifying the off-axis wavefront itself. In this paper, we analyze the use of non-planar transmission gratings recorded using a conjugate geometry (opposite propagation direction from operation) to modify the off-axis wavefront. Diverging sources are used as conjugate object and reference beams respectively. The spherical waves are incident at the lens and the grating is recorded at the entrance aperture of the solar concentrator. The on-axis source is adjusted to produce an on-axis planar wavefront on the hologram plane. The off-axis source is approximated to a diffraction limited spot producing a non-planar off-axis wavefront on the hologram plane. Illumination with a planar AM1.5 spectrum reproduces an off-axis diffraction-limited spot on the focal plane. This paper presents ray trace and coupled wave theory simulations used to quantify the reduction in losses achieved with aberration correction. Also, we present a design for a solar simulator based on this geometry.

8821-7, Session 2

Limitations of multiplexed volume holograms as broadband dispersive elements for solar concentrators

Gregory B. Ingersoll, Di Lin, James R. Leger, Univ. of Minnesota, Twin Cities (United States)

Using diverse bandgap photovoltaic cells can improve solar conversion efficiency, but these systems also require efficient dispersive optics to direct portions of the solar spectrum onto the appropriate optimized cells.

One advantageous technique for spectrum spitting employs transmission-mode volume holograms. These grating structures can be made highly efficient but are often also highly selective, interacting only with narrow wavelength bands and narrow ranges of incidence angles. To widen the bandwidth for a solar concentration application, planar volume gratings can be multiplexed in a single HOE. But this technique has its limits.

In this work we use an extended coupled-mode model to show how multiplexed gratings interact with one another leading to reduced efficiency in the diffraction orders of interest as well as increased stray light in certain conditions. This technique reveals effects that cannot be seen through superposition of single grating models, which suggests that multiplexed gratings must be treated simultaneously when designing such a system.

Further, these inter-grating interference effects are demonstrated experimentally in dichromated gelatin. Multiplexed gratings are constructed in the lab, and grating diffraction efficiencies are measured at multiple laser wavelengths suggesting the expected results when applying these techniques to a continuous spectrum. Measurements are compared with theory, and the mathematical model is extended to simultaneously treat spurious reflection gratings from the construction process as well as harmonic effects that can arise as a result of the limited dynamic range of the recording medium.

8821-8, Session 3

Single element point focus spectral splitting concentrator with CIGS multiple bandgap solar cells

Marco Stefancich, Ahmed Zayan, Matteo Chiesa, Masdar Institute of Science & Technology (United Arab Emirates); Stefano Rampino, Istituto dei Materiali per l'Elettronica ed il Magnetismo (Italy); Carlo Maragliano, Masdar Institute of Science & Technology (United Arab Emirates)

The combination of optical concentration, spatial spectral splitting and the use of multiple cells of suitable bandgap, allows to achieve extreme PV conversion efficiency [1] and high concentration modules have been designed employing separate elements for concentration and splitting [2].

We recently demonstrated a proof of concept approach where a single low cost refractive optical element is employed [3] for simultaneous splitting of sunlight and linear concentration at moderate levels.

We propose here point focus higher concentration version of spectral splitting/concentrating element coupled with multiple inexpensively developed Cu(InxGa1-x)Se2 solar cells designed for concentration [4]. The cells absorbers are developed in a single step by Pulsed Electron Deposition method [5] and different bandgaps are achieved by suitable In-Ga balancing. The concentrator is obtained by injection molding and can be mass produced at low cost.

This approach hints to the possibility of developing a low cost framework for high efficiency spectral splitting photovoltaics systems.

Theoretical framework, simulations and preliminary experimental results will be discussed.

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8821-9, Session 3

Spectrum splitting photovoltaics: light trapping filtered concentrator for ultrahigh photovoltaic efficiency

Emily D. Kosten, John Lloyd, Emily C. Warmann, Harry A. Atwater Jr., California Institute of Technology (United States)

While monolithic multijunction solar cell approaches have been quite successful, current and lattice matching requirements limit the maximum possible achievable efficiencies. Spectrum splitting, where light is optically distributed among subcells with differing bandgaps,

avoids these constraints and offers a route to achieving higher efficiencies (>50%). We investigate a spectrum splitting approach where concentrated sunlight is trapped in a textured dielectric slab and then selectively coupled into underlying solar cells of different bandgaps through omnidirectional filters. We develop a multipass optical model to find regimes of high optical efficiency based on parameters such as slab refractive index, number of subcells, and angle restriction of light escape from the slab. Based on these results and filter design considerations, we describe a specific design featuring an SiO_2 textured slab coated with angle restricting incoupling elements based on compound parabolic concentrators and two underlying triple junction solar cells, one with bangaps from 1.32 to 2.1 eV and the other with bandgaps from 0.71 to 1.12eV . Using the multipass model in conjunction with modified detailed balance calculations, we find module efficiencies exceeding 50% are possible with an acceptance angle restricted to 20° or less and concentrations of a few hundred suns. Finally as proof of concept, we demonstrate a nearly omnidirectional filter design for use underneath the SiO_2 slab. Based on alternating layers of TiO_2 and SiO_2, we achieve angle averaged reflectivity greater than 90% within the reflection band and angle averaged transmission of approximately 90% within the transmission band.

8821-10, Session 3

Concentrating and spectrum splitting optical device in high efficiency CPV module with five bandgaps

Jerker Y. Taudien, Ludwig A. Kern IV, Vertex Solar (United States)

There is a need for a high efficiency low cost solar energy conversion system. Currently, most concentrating photovoltaic (CPV) systems concentrate the solar spectrum onto triple junction cells to strive for high conversion efficiencies and low cost. Other approaches to high efficiency use spectrum splitting. Triple junction systems are limited in efficiency and spectrum splitting systems are usually too costly for mass production. The objective is to design a spectrum splitting solar concentrator, using reverse ray tracing methods, to overcome the efficiency and cost limitations of current systems by using a single low cost optical device to concentrate and split the solar spectrum onto a large number of target photovoltaic (PV) cells. Dispersive properties of standard optical materials, such as glass or plastic, are utilized to achieve the desired spectral separation. Reverse ray tracing is used to simultaneously optimize the shape of the top and bottom interfaces of the solar concentrator to achieve the desired split spectrum at the target PV cells. Additional strategies to increase system efficiency and minimize optical losses, including draft surface shading and corner rounding losses, are explored. A CPV module, including the spectrum splitting solar concentrator and five PV cells of different bandgaps, is proposed. This spectrum splitting CPV system has a calculated aggregate cell conversion efficiency that exceeds 45%, has the potential to be mass produced, and meets the need for a high efficiency low cost solar energy conversion system.

8821-11, Session 3

Polyhedral specular reflector design for ultra high spectrum splitting solar module efficiencies (>50%)

Carissa N. Eisler, Emily D. Kosten, Emily C. Warmann, Harry A. Atwater Jr., California Institute of Technology (United States)

One pathway to achieving ultra high solar efficiencies (>50%) is employing a spectrum splitting optical element with more junctions (>6) and some concentration (100-500 suns). We propose a design to obtain these efficiencies, employing basic specular reflection to split and divide the light onto appropriate subcells. The polyhedral specular reflector incorporates a high index parallelepiped with seven subcells. The subcells are placed around the parallelepiped such that light entering at normal incidence encounters the subcells in order from highest to lowest bandgap, with the ray path reflecting at a 90° angle until the light is fully absorbed.

Using detailed balance calculations that account for realistic cell performances, we find that concentration is necessary for >50% module efficiency. However, concentration increases the range of input angles, causing the misallocation of photons. These optical losses can be mitigated by using a higher index parallelepiped, such as TiO_2 or GaP, as refraction reduces the angular spread of light. For example, for the same optical losses, more than twice the concentration can be accommodated for a parallelepiped made of GaP than of glass. We analyze these losses and optimize the design using modified compound parabolic concentrators. We find that moderate concentration designs (90-170x) achieve 50% module efficiency, with GaP achieving the maximum efficiency at 53%. However, some junctions may parasitically absorb light not intended for that junction, reducing overall efficiency. We quantify these losses and demonstrate initial designs for filters to prevent unwanted light from entering each junction.

8821-12, Session 4

Solar internal lighting system with an automated solar tracker for daylight harvesting

Upkar Kumar, Retheesh Raj, Kavitha K. Gopalan, Vadakedathu P. N. Nampoori, Animesh Aaryan, Cochin Univ. of Science & Technology (India)

This paper reports the design and realization of a solar internal lighting system equipped with a solar tracker for sunlight harvesting during daytime. An experimental prototype was designed and results have proven an excellent performance of the developed system. The system mainly consists of two parts: solar concentrator and a solar tracker. The solar concentrator has been designed by pasting small pieces of mirror on a parabolic dish which focuses the light coming from sun at its focus. Optical fibers have been used to guide the focused light inside the building after removing the infra-red component using a water column. The other end of the fiber is connected to a fiber texture which is used for lighting inside the building. A simple solar tracking system has been implemented here using a programmed stepper motor which follows the Sun, right from dawn, throughout the day, till evening, and starts all over again from dawn next day. This tracking mechanism helps to enhance light collecting efficiency of the parabolic solar light collector. A micro-controller sends control pulses to stepper motor according to the program. The controller is programmed using AVR (Advanced Virtual RISC) Dragon which is connected to PC through a standard USB port. The source code has been written in C language. IC ULN2003A has been used to drive the motor. There is practically no maintenance costs associated with the system. Thus it is expected that the present 'Solar lighting System' will to be an efficient system for interior lighting during the day.

8821-13, Session 4

An introduction to the Amonix 8700 Solar Power Generator *(Invited Paper)*

Adam P. Plesniak, Vahan Garboushian, Amonix Inc. (United States)

From 2009 through early 2012, Amonix installed nearly 40MW of the flagship 7700 Solar Power Generator product in many locations all across the southwestern USA. Since completion of these projects, Amonix has been adapting lessons learned from the 7700 scale-up and new CPV technologies into the company's 8700 Solar Power Generator, to be released in late 2013. The presentation will focus on the new features of the 8700 product, including drastically higher performance and lower cost. This includes discussion about methodologies used in the design process and how these were used to improve the product.

The presentation will also aim to discuss in summary the performance stability of the 7700 products currently in the field. Overall, the presentation will focus on what is being done at Amonix in the 8700 product to keep CPV competitive in the solar marketplace.

8821-14, Session 4

Concept and initial design of a stationary concentrator photovoltaic system based on a mirror array

Takumi Kamimura, Ryo Amano, Ichiro Fujieda, Ritsumeikan Univ. (Japan)

We propose a stationary module in which a mirror array is inserted between a lens and a solar cell. Each mirror is set up so that the light passing the principal point of the lens reaches a fixed point on an exit plane and that the length of its optical path is equal to the focal length of the lens. The light passing the other points in the lens reaches other mirrors. If the reflected light mostly reached the area near the fixed point, a slightly larger solar cell would harvest it. We have carried out ray tracing simulations to see how the optical power is distributed on an exit plane of such a module. The model consists of a hollow rectangular parallelepiped containing a mirror array, a plano-convex lens attached to the top plane of the parallelepiped, and a detector attached to one of the side planes. A light source generates parallel beams with various directions defined by the declination angle and the hour angle. Although the irradiance distribution at the exit plane depends on these angles, the basic concept of confining the optical power inside a certain area is demonstrated. Further studies on its design would improve its light utilization. For example, the rays with large incident angles suffer from total internal reflection at the bottom of the lens. Filling the hollow parallelepiped by a material with a matching refraction index solves this problem.

8821-15, Session 5

9-fold Fresnel-Köhler concentrator for increased irradiance uniformity on high concentrations

João Mendes-Lopes, Univ. Politécnica de Madrid (Spain); Pablo Benítez, Light Prescriptions Innovators, LLC (United States); Pablo Zamora, Juan C. Miñano, Univ. Politécnica de Madrid (Spain)

Non-uniform irradiance patterns created by Concentrated Photovoltaics (CPV) systems over Multi-Junction Cells (MJC) can originate significant power losses. Furthermore, when chromatic aberrations between irradiance distributions over the different MJC sub-cells are significant, power losses increase considerably, especially when considering 4, 5 and 6 junction cells.

Recent advances in optical designs for CPV, namely Fresnel-Köhler (FK) technology, proven that a spectral balanced high irradiance uniformity is achievable for systems of 850-1000x and large acceptance angle. However, when aiming for larger concentrations, irradiance uniformity decreases for the same optical design family.

Interest on Silicon-on-Glass (SoG) lens has been growing due to the combination of mass production simplicity (injection molding) and high resistance to external factors. SoG lens refractive index is affected by thermal changes, affecting considerably spectral balance of irradiance distributions.

A new CPV optical design, with large acceptance angle and prepared to overcome these effects, is presented.

The 9-fold Fresnel-Köhler (FK-9) 1000x concentrator, with acceptance curve of 1.19º, is based on a SoG nine sectors Fresnel lens combined with a Secondary Optical Element with nine refractive free-form surfaces.

The advanced design was developed such that the performance features (concentration-acceptance products - CAP- between 0.62-0.66, depending on design parameters, excellent irradiance uniformity and spectral distribution) are kept when concentration increases to 2000x and when SoG lens refractive index is affected by thermal effects, revealing excellent tolerance to manufacturing and external factors.

This paper will show the main design features, along with realistic performance simulations considering all spectral characteristics of the elements involved.

8821-16, Session 5

Development and characterization of an FK photovoltaic concentrator for maximum conversion efficiency

Maikel Hernández, Juan F. Vilaplana, Light Prescriptions Innovators Europe, S. L. (Spain); Pablo Benítez, Univ. Politécnica de Madrid (Spain); Rubén Mohedano Arroyo, Light Prescriptions Innovators Europe, S. L. (Spain); Pablo Zamora, Juan C. Miñano, Univ. Politécnica de Madrid (Spain)

Most cost-effective concentrated photovoltaics (CPV) systems are based on an optical train comprising two stages, the first being a Fresnel lens. Among them, the Fresnel-Köhler (FK) concentrator stands out owing to both performance and practical reasons. The FK features a set of advanced characteristics, desirable in CPV: high optical efficiency, large acceptance angle, insensitivity to manufacturing tolerances, very good irradiance uniformity on the cell surface and easy cell to SOE gluing. All these features are achieved without the need of any kind of additional complexity: this system is still a Fresnel based system whose primary concentrator stage can be manufactured in large inexpensive panels and, as other CPV systems, utilizes a secondary lens to attain the necessary enhanced characteristics to achieve cost-effectiveness: high CAP to minimize the investment of solar cells but assuring the performance at array level. Moreover, FK POE can be developed on both extended CPV materials: PMMA and Silicone-on-Glass (SoG).

Recent on-sun measurements carried out on an FK mono-module prototype have already shown outstanding results, achieving electrical efficiencies over 34% (no AR coating applied on SOE) for the SoG case. Since in this case a first prototype of this design has been used, optical elements are not perfectly optimized yet. This fact brings enough room to predictably go over efficiency values of 35% (additionally applying an AR coating on the SOE) during the next months.

8821-17, Session 5

Design of a etendue-cascading solar concentrator

Jhe-Syuan Lin, Chao-Wen Liang, National Central Univ. (Taiwan)

Solar concentrators are often used in conjunction with III-V multi-junction solar cells for the competitive cost and the better efficiency. A successful concentrator design can significantly reduce the per watt cost of generated solar energy. This research paper describes a novel concentrator design that combines the concepts, and thus the advantages, of both the refractive type and the reflective type concentrator.

This design adopts the novel Etendue-Cascading concept that allows the optical flux from all concentric segments of the entrance pupil to be collected and transferred to the solar cell. This novel concept enables the system to perform at its theoretical Etendue maximum limit. The increased Etendue of the system results in a solar concentrator design with higher flux concentration ratio while maintaining a minimal optical system thickness and zero back focal distance, and thereby reducing the per-watts cost.

The optical design resulted in an aspect ratio of 0.25, geometrical concentration ratio of 625 times while the optical delivery efficiency is as high as 78% and the acceptance angle of 1.6 degrees. The concentrator is also featured with zero back focal distance for easier alignment and relaxed manufactured tolerance.

8821-18, Session 5

Solar spectral variations and their influence on concentrator solar cell performance: a comparative study between tandem and spectrum splitting parallel junctions

Lirong Z. Broderick, Brian R. Albert, Brian S. Pearson, Lionel C. Kimerling, Jurgen Michel, Massachusetts Institute of Technology (United States)

Traditional multi-junction concentrator solar cells use a vertically stacked tandem configuration. In recent years, parallel junctions where laterally aligned solar cells with differing bandgaps are used along with spectrum splitting optical elements stimulated renewed interest due to their potential of higher efficiency, less spectral sensitivity and more flexibility in materials choices. However, no quantitative data are available regarding the difference of efficiency and spectral sensitivity between the two types of junctions. For the first time, our research addresses these issues through a comparative study.

Direct normal solar spectra in a representative sunny site, Tucson, Arizona at 15-minute intervals throughout a whole year are calculated using the SPCTRAL2 model. Real-time meteorological data including aerosol optical depth and precipitable water vapor provided by AERONET for the year 2000, ozone amount obtained using the van Heuklon model, and geographical parameters of Tucson (latitude, longitude and elevation) are used as input for the spectral calculations. The corresponding efficiencies of tandem and parallel junctions under 500X concentration are computed for each spectrum. Both junction structures comprise the same materials, InGaP, GaAs and Ge, and are each optimized to the AM1.5D standard spectrum, under which the parallel junction achieves an efficiency 1.9% absolute (and 4.6% relative) higher than the tandem junction. The two junctions are compared for their hourly, daily, monthly, and yearly average efficiencies. It is found that the yearly average efficiency of the parallel junction is 4.2% absolute higher than for the tandem cell, corresponding to an annual energy production difference of 71.6 MWh/m2.

8822-1, Session 1

Progress in advanced solar to hydrogen production technologies *(Invited Paper)*

Eric L. Miller, Sara Dillich, Erika Sutherland, Sarah Studer, Katie Randolph, David Peterson, U.S. Dept. of Energy (United States)

The US Department of Energy's (DOE) Fuel Cell Technologies Office (FCT) has made significant progress in fuel cell technology advancement and cost reduction, highlighted by reducing the cost of automotive fuel cells by more than 80% since 2002. The next major challenge is the widespread production of affordable renewable hydrogen. FCT programs aim to address this challenge with a balanced research and development (R&D) portfolio of both near- and longer-term hydrogen production technologies. The portfolio design is informed by ongoing R&D progress, through technoeconomic analysis, and with expert recommendations (such as those from the 2012 Hydrogen Production Expert Panel, a subcommittee of the Hydrogen and Fuel Cell Technical Advisory Committee). Central to the long term vision for renewable hydrogen are the solar-to-hydrogen conversion processes, including the photoelectrochemical, biological and thermochemical routes. To be successful, these pathways require continued advances in novel materials, nano-structures and interfaces (organic and inorganic). Cross-cutting research collaborations across DOE programs and other federal agencies are leading to important progress in the materials development for the solar-hydrogen production technologies, which is discussed in this presentation.

8822-2, Session 1

Modeling of complex phenomena in materials science: challenges and successes *(Invited Paper)*

Biplab Sanyal, Uppsala Univ. (Sweden)

In this talk I will discuss the challenges and successes in theoretical materials science with a focus on energy related research. The limitations of standard approximations in single-particle based materials specific theories will be mentioned along with remedies using sophisticated many body based methods. Issues like quantum confinement, band gaps, electron correlation in oxides, complex magnetism etc. will be discussed. In this regard, I will mention relation to several experimental techniques with a focus on synchrotron based measurements.

8822-3, Session 1

Optimisation of photo-active oxides and composites through solution based processing *(Invited Paper)*

Gunnar Westin, Uppsala Univ. (Sweden); Kjell Jansson, Stockholm Univ. (Sweden); Annika Pohl, Koroush Lashgari, Michael Leideborg, Uppsala Univ. (Sweden)

For practical use of catalysts for solar fuels, solar cells and photo-assisted cleaning of water and air, robust, low cost routes to advanced complex materials are a requisite. These multi-functional devices should both be effective in photon generation of holes and electrons, transport and catalysis of surface reactions, where different functions most probably need to be optimised in different parts of a nano-structure. Quantum confinement in typically less than 3 nm sized oxide systems may also be an efficient means for improved properties, which puts high demands on the precision of the processing routes. For such demands solution based routes are the best suited, but there is a need for further development of well understood, flexible routes to high quality, complex nano-structures. Here we discuss solution based processing routes of different kinds of doped and non-doped oxide and metal nano-particles, thin- and ultra thin films. The oxide systems involve doped and non-doped Fe_2O_3, TiO_2, ZnO, spinel and perovskite nano-particles, films and ultra-thin films, as well as metal nano-particles and ultra-thin films. The processes and materials were studied by a wide array of techniques including; SEM, TEM, XRD, TGA, DSC/DTA, IR-, Raman and UV-Vis-NIR spectroscopy, and connected with band-structure and properties.

8822-4, Session 2

First-principles studies of TiO_2 for photocatalysis *(Invited Paper)*

Chris G. Van de Walle, Poul Moses, Joel B. Varley, Anderson Janotti, Univ. of California, Santa Barbara (United States); André Schleife, Lawrence Livermore National Lab. (United States)

TiO_2 is a material of increasing interest in electronics, optoelectronics, and chemistry, with applications in high-k dielectrics, solar cells, and (photo)catalysis. Rutile TiO_2 has a wide band gap of 3.1 eV and exhibits a tendency for unintentional n-type conductivity. Understanding and controlling the conductivity and absorption characteristics of TiO_2 is a key step toward the wider application of this material. Here we use advanced first-principles calculations to address the structural and electronic properties of bulk and surface, as well as point defects and impurities in TiO_2. The use of a hybrid functional in density functional theory allows us to overcome the "band-gap problem". Optical spectra are calculated using many-body perturbation theory by solving the Bethe-Salpeter equation (BSE). We discuss the role of nitrogen and sulfur in changing the absorption properties.

Collaborations with F. Bechstedt, C. Franchini, G. Kresse, and P. Rinke are gratefully acknowledged.

8822-5, Session 2

Fundamental aspects of disorder-engineered titanium dioxide *(Invited Paper)*

Samuel S. Mao, Lawrence Berkeley National Lab. (United States)

This presentation will provide an overview of recent progress in the development of oxide-based photocatalytic and photoelectrochemical approaches for solar-driven production of hydrogen from water. The emphasis will be on fundamental aspects of disorder-engineered titanium dioxide nanoparticles, starting with an introduction of the basic electronic band structure resulted from disorder incorporation, followed by recent synchrotron radiation-based experiments aimed to provide an insight into the unique material that has shown significant activity of solar-driven hydrogen production.

8822-6, Session 2

Surface disordered metal oxide nanostructures for photoelectrochemical water splitting

Aadesh P. Singh, Indian Institute of Technology Delhi (India); Sanjay Mathur, Univ. zu Köln (Germany); B. R. Mehta, Indian Institute of Technology Delhi (India)

The use of metal oxide semiconductor as a solar energy harvesting element in photoelectrochemical cell for water splitting is a topic of growing interest for solar energy conversion to chemical fuel. Surface disordering in metal oxides at nano-level is a promising tool for altering optical absorption and carrier transport in metal oxide semiconductors which can be used an efficient photoelectrode in PEC cell for solar energy harvesting. Gas phase techniques offers a viable solution for overcoming thermodynamic impediments involved in thin film growth and disorder-engineering through in-suit molecule precursor-based plasma coatings of metal oxides and anisotropic hydrogen plasma treatment.

This talk will present how PE-CVD processed nanostructured films of different metal oxides open up new vistas of material properties, which can be transformed into advanced material technologies. Further, the effect of surface disordering of metal oxide nanostructures created by reducing hydrogen plasma treatment on optical, electrical and photoelectrochemical will be discussed.

8822-7, Session 3

Water structure and redox level alignment at the water/semiconductor interface from first principles *(Invited Paper)*

Marivi Fernandez-Serra, Philip B. Allen, Jian Liu, Luana Pedroza, Stony Brook Univ. (United States)

To achieve high photocatalytic oxidation activity in semiconductor surfaces two physical requirements need to be satisfied. The first, which is necessary, but not sufficient, is that candidates need to absorb light in the visible. The second is associated to the suitability of the conduction and valence band edges of the semiconductor for the overall water splitting reaction.

In this presentation I will show results from first principles molecular dynamics simulations of water at the interface of GaN and perovskite oxides semiconductors and will discuss how to accurately compute the alignment of the water electronic levels with respect of those of the semiconductor bulk. In particular, I will discuss how the first principles results are dependent both on the theory approximations (exchange and correlation functionals, including hybrid functionals) and on the adequate sampling of the structure of the liquid at the interface. When water dissociation occurs at the interface, new surface states can influence the path for the photo-hole transfer to water. I will also discuss the role of surface polarity and its link to the structure of the interfacial water. Our results will help to understand both the efficiency of certain surfaces on catalyzing the oxidation reaction and the relevance of surface acidity for prospect semiconductor photo-catalysts.

8822-8, Session 3

On quantum confinement effects in large bandgap semiconductors *(Invited Paper)*

Lionel Vayssieres, Xi'an Jiaotong Univ. (China)

The overview and the latest advances in quantum confinement effects and interfacial electronic structure of visible light-active all-oxide heteronanostructures for solar hydrogen generation by water splitting without sacrificial agent will be presented. The study includes the synthesis of highly oriented nanorod-based arrays at low temperature from aqueous precursors without any surfactant on various substrates, the bandgap and bandedge engineering of photoactive oxide semiconductors, their size dependent surface chemistry, conduction band orbital character and electrical properties as well as the in-depth understanding and engineering of the interfacial electronic structure by synchrotron-based studies of all-oxide heteronanostructures including orbital symmetry and crystal field splitting optimization for better efficiencies.

8822-9, Session 3

Towards a perfect system for solar hydrogen production: an example of synergy on the atomic scale

Ramy Nashed, Georgia Institute of Technology (United States) and The American Univ. in Cairo (Egypt); Jang Seung-Soon, Georgia Institute of Technology (United States); Yehea Ismail, Nageh K. Allam, The American Univ. in Cairo (Egypt)

The effect of metal doping on electronic band structure and charge carriers effective mass of Ta2O5 were studied using hybrid functionals in density functional theory. PBE0 hybrid functional proved to be very efficient in predicting the band structure with less than 5% error compared to experimental data. The bandgap decreases monotonically as the percentage of the dopant increases. Furthermore, the indirect bandgap behavior of Ta2O5 was found to initially increase on doping before it decreases again to its original value of pristine Ta2O5. We found that high percentage doping or even mixing with another metal is required in order to modify the band structure of Ta2O5. The effect of doping on the crystal structure was also studied. XRD measurements show that the crystal lattice tends to expand upon doping with metals with larger atomic radius than Ta and this effect is more pronounced as the dopant concentration increases.

8822-10, Session 3

Pulsed plasma deposition methods for photoactive ?-Fe2O3 hematite thin films

Stepan Kment, Zdenek Hubicka, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Josef Krysa, Institute of Chemical Technology (Czech Republic); Jiri Olejnicek, Martin Cada, Michaela Brunclíková, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Rodney J. Soukup, Natale J. Ianno, Univ. of Nebraska-Lincoln (United States)

Highly photoactive hematite (?-Fe203) thin films have been deposited by magnetron sputtering, high power impulse magnetron sputtering (HiPIMS) and hollow cathode plasma-jets. All these method are capable of producing crystalline films during the deposition process. Moreover, the crystalline plane orientation can be influenced. The films were characterized using a broad range of methods (XRD, Raman spectroscopy, XPS, AFM, SEM, etc.). The solar photocurrent measurements were done to assess the photoelectrochemical performances of the electrodes. The dependency of the pulsing frequency, current density and further deposition plasma parameters on the on the properties and photoelectrochemical activity of the films were discussed.

8822-11, Session 3

Cold gas spraying of semiconductor coatings for the photooxidation of water

Thomas Emmler, Helmholtz-Zentrum Geesthacht (Germany); Henning Gutzmann, Helmut-Schmidt Univ. (Germany); Mauricio Schieda, Helmholtz-Zentrum Geesthacht (Germany); Frank Gärtner, Iris Herrmann-Geppert, Helmut-Schmidt Univ. (Germany); Thomas Klassen, Helmut-Schmidt Univ. (Germany) and Helmholtz-Zentrum Geesthacht (Germany)

The switch of the energy production towards regenerative energies is currently of large general interest. Especially the production of hydrogen via photo induced water splitting is promising since it allows the storage of solar energy.

This contribution shows the potential of cold-gas-spraying for the production of photo-chemical electrodes employing photoelectrocatalysts for the water oxidation reaction (OER). Conventional methods of coating usually employ sol-gel methods and calcination to obtain a good binding of the coating to the substrate. In the cold-gas-spraying process particles are accelerated to high velocities in a laval nozzle. By the impact on the substrate the particles are deformed and build up an efficient interface to the back contact (analyzed e.g. by cross-section SEM). Cold-gas-spraying is a method for the direct coating of surfaces and does not make use of additives that have to be removed afterwards e.g. by a calcination step but allows the direct formation of a working electrode ensemble.

In first tests the "classical" photocatalyst Titanium dioxide was probed whose cold-gas sprayed films revealed similar activities compared to films derived from wet-chemical processes. This approach was extended to the photoelectrocatalyst hematite for the OER. Employing analytical methods like SEM, Raman, XRD and XPS in correlation with photoelectrochemical measurements the operation parameters of the cold gas spray process are discussed in terms of their influence on the photocatalytic properties of the semiconductor. Moving further to new materials based on TiO2 and hematite the problems of the coating stability are discussed.

8822-12, Session 4

Ceria chemistry at the nanoscale *(Invited Paper)*

Kersti Hermansson, Jolla Kullgren, Peter Broqvist, Uppsala Univ. (Sweden)

Ceria (CeO2) is used in solid oxide fuel cells and for the purification of exhaust gases in vehicle emissions control. Behind these technically important applications of ceria lies one overriding feature, namely ceria's exceptional reduction-oxidation properties enabled by the duality of the cerium, which toggles easily between Ce4+ and Ce3+ thanks to its 4f electron. Traditionally, much of the technical functionality of ceria has been ascribed to oxygen vacancies. However oxygen vacancies are not the only players [1]. We have performed extensive theoretical simulations of various flavors (quantum-mechanical calculations, force-field calculations, MD simulations, structure optimization with genetic algorithms, . . .) to explore the character and chemistry of ceria. In particular, experiments [2] have shown that small nanoparticles of ceria, with an average diameter of approximately 4 nm, possess a dramatically increased oxygen storage capacity (OSC) compared to larger particles. We find that - for such small particles - it is not explicit oxygen vacancies that govern the OSC, but instead it is governed by superoxo ions (O2-) that decorate the nanoparticle.

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8822-13, Session 4

Development of metal tungstate alloys for photoelectrochemical water splitting

Dixit Prasher, Marina Chong, Y. Chang, Hawaii Natural Energy Institute (United States); Pranab Sarker, Muhammad N. Huda, The Univ. of Texas at Arlington (United States); Nicolas M. Gaillard, Hawaii Natural Energy Institute (United States)

The last decade has witnessed about much efforts devoted to identify a suitable semiconductor to be integrated in an efficient, economical and stable photo-electro-chemical (PEC) system. Among the various materials, binary transition metal oxides are still considered to be a promising as most of them offer good ionic as well as electronic conductivity and are inexpensive to produce. But unfortunately, no binary oxide has yet fulfilled all the PEC criteria like optical function required to obtain maximum light absorption and photo-conversion efficiency simultaneously. To overcome the above situation, we demonstrate how density functional theory (DFT) can be of great boost in the category of new oxide-based PEC materials. As suggested by DFT, copper was first evaluated to form ternary CuWO4 mineral and also literature highlighted that addition of Copper to the host tungsten trioxide improves the visible light absorption. Several techniques were used to form this new PEC material (PVD, spray pyrolysis, solid state reaction), all leading to 2.2 eV band-gap n-type CuWO4 systems capable of generating photocurrent density of 0.5 mA.cm-2 at saturation (1 VSCE, pH10, AM1.5G). Furthermore, DFT calculations revealed that the addition of bismuth to form CuBiW2O8 mineral could suppress the unfilled mid-gap states present in CuWO4 resulting in less charge trapping and also would improve the electron mobility with more dispersed conduction band. To validate this hypothesis, CuWO4 and CuBiW2O8 pellets were prepared with mortar mix nanopowders of CuO, WO3 and Bi2O3. After annealing the pellets in air at 8500C for 6 hours, resistance measurement was carried out at various temperatures using impedance spectroscopy analysis. Electrical measurements performed on both CuWO4 and CuBiW2O8 ceramic pellets confirmed an increase in electrical conductivity by a factor of 100 after addition of bismuth (from 5.7?10-8 S.cm-1 to 3.8?10-6 S.cm-1). Research is currently focused on CuBiW2O8 thin films synthesis to evaluate the PEC performances of this new material class.

8822-14, Session 4

Photoelectrochemical performance of doped BiVO4 thin-films deposited by spray pyrolysis

Stephen K. Holland, David J. Lawrence, Thomas C. DeVore, James Madison Univ. (United States)

The solar water splitting performance of thin-film BiVO4 photoanodes deposited by low-cost spray pyrolysis deposition exhibits a significant dependence on the chemical precursor solution formulation, deposition substrate material, and post-deposition treatment methods. BiVO4 thin films were deposited on indium tin oxide (ITO), fluorine doped tin oxide (FTO), and tungsten oxide (WO3) by spray pyrolysis of aqueous solutions of Bi(NO3)3 and VOSO4. N-type films were produced by including various ratios of silicotungstic acid or ammonium metatungstate in the precursor solutions. The resulting BiVO4 films exhibited a porous microstructure. X-ray diffraction measurements confirmed that monoclinic BiVO4 was formed following 500ºC annealing in air. The photoelectrochemical (PEC) water splitting performance of the photoanode samples was evaluated in a three-electrode cell under AM1.5 illumination of 0.1 W/cm2 from a solar simulator. Films that received additional annealing in 3% H2 produced the largest measured photocurrent densities, exceeding 2 mA/cm2 with an applied bias of 1.5 V. Results indicate that the substitution of tungsten for vanadium rather than bismuth in the precursor solutions produces films with better PEC performance. Results indicated that tungsten doping resulted in a photocurrent reduction relative to the undoped samples. Results also indicated a strong correlation between the PEC performance of the photoanodes and the substrate materials on which the BiVO4 was deposited. The effects of tungsten and molybdenum doping of the BiVO4 films as well as heterojunction and material combination effects are the subject of ongoing investigations.

8822-15, Session 4

Control over crystal growth and morphology of nanostructured BiVO4 films for water photo-splitting

Abdelkrim Chemseddine, Roel Van de Krol, Lichao Jia, Tayfun Mete, Ursula Michalczik, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

Bismuth acetate and vanadium oxo isopropoxide were used as precursors. Their reactivity was adjusted by adding chelates and therefore controlling the nucleation and growth processes of BiVO4. The films were grown on a seed film in a chemical bath by controlling the temperature. Compared to films made by spin-coating or spray pyrolysis, XRD shows a preferred orientation of BiVO4 crystallites with the monoclinic crystal structure. Scanning electron microscopy shows well defined crystals with sharp edges and smooth surfaces. Highly transparent and dense films or highly nanoporous films can be obtained by adjusting the composition of the precursors solution.

Multilayers films can be prepared by spin-coating. In this contribution, the texture of the final film, the porosity, the grain boundaries and the orientation of the crystallites depend strongly the intermediate heat-treatment and on the final heat-treatment of the final multilayers films. The photoactivity of the films is investigated using surface photovoltage, followed by photoelectrochemical measurements.

8822-16, Session 5

Challenges and opportunities in the atomistic modelling of interfaces for energy harvesting *(Invited Paper)*

Feliciano Giustino, Univ. of Oxford (United Kingdom)

Understanding and designing functional interfaces has become a priority in many areas of science and technology, ranging from photovoltaics and photocatalysis to electronics and biosensing. A fundamental property of functional interfaces is the alignment of the electron energy levels between the two materials. Such alignment underpins several important phenomena, eg charge-transfer doping, carrier injection, and exciton dynamics. In the context of solar energy technology the level alignment determines the ability of the interface to transfer energy from a donor to an acceptor by exchanging photoexcited charges. While the physics of the energy-level alignment at conventional semiconductor heterojunctions is currently well established, little is known about functional interfaces involving metal oxides and soft materials such as polymers and light-harvesting molecules. Here I will review our recent activity [1-5] in the computational modelling of TiO2 and ZnO interfaces of current interest for nanostructured solar cells, and of experimental probes such as X-ray photoemission spectroscopy and ultraviolet photoemission spectroscopy. In this area the first challenge that we have to face is to determine the structure of the interface at the atomic scale. Here standard optimization techniques are bound to fail due to the large number of possible interface morphologies. I will argue that a possible way forward is to build interface models by reverse-engineering experimental data using first-principles computational spectroscopy. This notion will be illustrated by discussing core-level photoemission at interfaces between TiO2 and metal-organic chromophores. The second challenge is the development of robust computational methods for studying the electronic structure of functional interfaces. In this case standard density-functional techniques are rarely in quantitative agreement with photoemission data and more sophisticated approaches become necessary. This will be illustrated by discussing semiconductor-polymer [4] and metal-oxide/molecule interfaces [5]. Here I will briefly review our activity in the area of many-body perturbation theory techniques (GW method), and in particular the use of quasiparticle methods in the case of transition metal oxides with localized d electrons [3].

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8822-17, Session 5

Toward in-situ time-domain x-ray studies of interfacial photochemistry *(Invited Paper)*

Oliver Gessner, Lawrence Berkeley National Lab. (United States)

Interfacial photochemistry is governed by the flow of charge, mass, and energy among molecules and between molecules and condensed phase substrates. By definition, the quest for a deeper understanding of interfacial photochemical processes is directly related to the capability to monitor non-equilibrium dynamics of complex systems in electronically and/or vibrationally excited states. Time-domain x-ray spectroscopy techniques offer new opportunities to unravel the fundamental electronic and nuclear dynamics that underlie chemical and electronic function in processes such as photoelectrochemical water splitting or photovoltaic power generation. The simultaneous element specificity and chemical sensitivity of x-ray transitions in combination with the time-structure of accelerator-based x-ray light sources provides real-time access to transient oxidation states and local bonding motives with atomic pinpoint accuracy. Recent femtosecond time-resolved x-ray photoelectron spectroscopy (TRXPS) measurements at the Linac Coherent Light Source (LCLS) and the Advanced Light Source (ALS) provide a molecular scale perspective of the visible light induced transient oxidation states of N3 dye molecules adsorbed to nanocrystalline ZnO, one of the key components of dye-sensitized solar cells. The underlying physics are explored in a concerted effort of TRXPS experiments and ab-initio calculations of the interfacial electronic structure. Building on these proof-of-principle studies, current efforts focus on the extension of time-domain x-ray techniques toward in-operando studies of photochemical processes. A pathway will be outlined to study the dynamics of interfacial states at a hematite-electrolyte interface in an operational photoelectrochemical cell by time-resolved x-ray absorption spectroscopy (TRXAS).

8822-18, Session 5

Semiconductor quantum dot sensitisation: application to solar energy conversion *(Invited Paper)*

Yasuhiro Tachibana, RMIT Univ. (Australia)

Semiconductor quantum dot (QD) is one of the most attractive nanomaterials to be utilized for solar energy conversion devices. Similar to dye sensitised solar cells, sensitization of metal oxide nanostructures by QDs can be realized. The sensitised nanostructure maximises the light harvesting efficiency and charge separation process, thereby being suitable for the device design. This configuration has been intensively studied to be applied for QD sensitised solar cells, and possibly applicable to solar water splitting processes.

The function of QD sensitised device is controlled by kinetic processes of the charge separation and charge recombination. For example, the device performance can be improved by accelerating the charge separation process and retarding the recombination process. However, the control of these reaction kinetics has rarely been studied, and the mechanisms of these reactions have not been well understood. In this presentation, we will demonstrate relationship of the QD nanostructures with the interfacial electron transfer reactions by employing time-resolved laser spectroscopies.

Several types of QDs with a narrow size distribution are synthesized to control the potential energy levels of the conduction and valence bands. Here we employ TiO2 nanocrystalline films, which are commonly used for the sensitised solar cells. The structure at the QD/TiO2 interface is modified to control electronic coupling between the QD and the TiO2. These QD sensitised TiO2 films are employed for transient laser spectroscopies.

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8822-19, Session 5

Kinetic studies of water oxidation on ?-Fe2O3 photoanodes

Florian Le Formal, Stephanie R. Pendlebury, James R. Durrant, Imperial College London (United Kingdom)

A combination of transient absorption spectroscopy and photo-electrochemical methods has been performed on iron oxide photoanodes to investigate the limitations of this material for water splitting.

Hematite, or ?-Fe2O3, is widely recognized as a promising candidate material to produce hydrogen from the Sun because of its low cost and high chemical stability. However the fall off in light absorption at long wavelengths and the poor charge carrier conductivity observed in iron oxide have been major drawbacks to implement this material in a water photolysis device. Recent advances in film preparation involving addition of dopants, increasing the electron conductivity, and nanostructuring strategies have substantially increased the performance of hematite electrodes. This enhancement has been mainly related to the reduction of the distance between where holes are photogenerated and where they react.

The second main limitation of hematite is the large overpotential required to drive the oxygen evolution reaction (O.E.R.) on its surface. This has been assigned to the slow reaction kinetics resulting in positive charge accumulation at the semiconductor electrolyte interface. Additionally to reduce the space charge layer, the accumulation can increase the competition between the reaction of holes and other detrimental processes such as charge trapping and charge recombination. Photo-electrochemical and optical spectroscopies have been performed to characterize the different processes occurring for photogenerated charges on the hematite surface. The different techniques used in addition to the different time scales scrutinized, help to distinguish the several reactions involved and to elucidate the origin of the low solar-to-hydrogen energy conversion efficiency.

8822-20, Session 6

In search of optimal photoelectrode: microscopic property of liquid-solid interfaces studied from first principle *(Invited Paper)*

Tadashi Ogitsu, Lawrence Livermore National Lab. (United States)

The surface morphology of III-V semiconductors such as GaP, InP, and GaInP2 were studied with ab-initio DFT total energy calculations. Several surface structural motifs, with and without oxygen or hydroxyl, were identified as likely to be present at the real electrode surface based on energetics. Contrasting chemical properties of these motifs for a water molecule adsorption were observed: M-O-M (M=Ga or In) motif initiates dissociative adsorption of water, while M-O-P (M=Ga or In) does not.

The water-semiconductor (GaP or InP) interfaces were studied using the ab-initio molecular dynamics simulations (MD). We find that the consistent behavior on the chemical activities of surface motifs in our interface MD simulations: M-O-M is reactive, while M-O-P is not. Detailed analysis on the properties of interfacial water was performed on the hydrogen bonding network topology, on the density profiles, on the rotational auto-correlation time, on the hydrogen bond dissociation-association frequency. The detail, particularly on the comparison between GaP and InP, will be discussed in the presentation.

Bridging between the atomistic simulation results and the reality is a major challenge in PEC field. The recent advancement on X-ray based spectroscopy technique made it possible to obtain atomistic insight on the chemical environment of the elements of our interest under the device operation condition. We have investigated on the computational X-ray absorption/emission spectrum for systems of our interest using the method developed by Prendergast of The Molecular Foundry, LBNL. The simulation procedure, results and interpretations will be discussed at the presentation.

8822-21, Session 6

Water-induced modifications of GaP(100) and InP(100) surfaces studied by photoelectron spectroscopy and reflection anisotropy spectroscopy

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The high photoconversion efficiency of III-V semiconductors makes them promising absorber materials for solar water splitting, especially in multi-junction approaches such as GaP(N)/Si [1]. A microscopic understanding of the semiconductor-electrolyte interface is crucial for a knowledge-based device design [2].

We explore the electronic and morphologic modifications of GaP(100) and InP(100) surfaces induced by the exposure to water in situ with reflection anisotropy spectroscopy (RAS). To this end, well-defined III- and V-rich surfaces were prepared by metal-organic vapour phase epitaxy (MOVPE) using in situ RAS to control the growth [1], and transferred contamination-free to UHV for further analysis. Water was adsorbed in a dedicated UHV chamber and its impact on the surface reconstruction was monitored in situ with RAS.

In-system LEED and photoelectron spectroscopy analysis before and after water exposure show that especially P-rich surfaces, which are typical for MOVPE preparation, are more stable than e.g. UHV-cleaved surfaces [3]. Subsequent annealing in N2 and H2 VPE ambient reveals that InP tends to form an ordered oxide. The P-rich surface reconstruction of GaP, on the other hand, can be largely restored upon annealing in H2. Our findings could lead to a better understanding of initial surface modification/oxidation, contributing vitally to in situ surface functionalisation strategies [4].

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8822-22, Session 6

Developing high quality BiVO4 thin film for photoelectrochemical study *(Invited Paper)*

Le Chen, Lawrence Berkeley National Lab. (United States); Esther Alarcon-Llado, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Ian Sharp, Mark Hettick, Yongjing Lin, Joel W. Ager III, Lawrence Berkeley National Lab. (United States)

BiVO4 (BVO) has attracted more and more attention as a potential photoanode candidate for photoelectrochemical (PEC) water splitting. However, according to the literature, most of BVO was synthesized in bulk by solution based methods. There lacks a high quality thin film synthesis method for BVO, which leads to a lack of fundamental study of electrochemical, electronic and optical properties of BVO.

In JCAP, we have successfully developed high quality BVO thin films by vapor deposition methods as sputtering and chemical vapor deposition

(CVD). For both of the synthesis methods, the control of stoichiometry is most critical and challenging since Bi and V has very different thermal conductivities. We also found out the different stoichiometry can give rise to different electronic conductivity and PEC performance. The structure and stoichiometry of the thin films were characterized by XRD, Raman, SEM and XPS. The PEC performance was evaluated by IV curve (with or without light), impedance as well as IPCE. Furthermore, we were able to carry out some fundamental studies of electronic and optical properties including diffusion length, surface states and carrier dynamics on the deposited thin films by using Surface Photovoltage (SPV) and Transient Absorption Spectroscopy (TA). The attempt to improve BVO PEC properties such as adding hole blocking layer, introducing W or Mo doping as well as coupling with OER catalysts were also going to be presented in the talk.

8822-23, Session 7

Exploring electrochemistry from first-principles with simulated core-level spectra *(Invited Paper)*

David Prendergast, Lawrence Berkeley National Lab. (United States)

In order to develop reliable insight into the working principles of electrochemical systems, one needs chemical model which can be validated against in situ characterization. Often, x-ray spectroscopy is applied, due to its elemental specificity and sensitivity to local electronic structure around the excited atom. However, such techniques probe electronic structure and not atomic structure, and rely on interpretation to make connections to chemical models. We have developed a first-principles approach to simulate x-ray spectroscopy using constrained density functional theory that is applicable to condensed phases. We provide several examples of the application of this method to problems in electrochemistry and photoelectrochemistry, illustrating the invaluable insight such methods provide for unraveling the meaning in spectroscopy and elucidating the mechanism of materials under bias and illumination.

8822-24, Session 7

The search for the optimal PEC material, soft x-ray spectroscopy, and the band gap *(Invited Paper)*

Clemens Heske, Univ. of Nevada, Las Vegas (United States) and Karlsruhe Institute of Technology (Germany)

The search for the optimal material for photoelectrochemical water splitting (PEC) can likely be accelerated by adopting an insight-based approach. For this, sophisticated characterization is needed, such that subtle modifications in the PEC material, which can lead to significantly different PEC performance, can be identified and understood.

This presentation will demonstrate that soft x-ray spectroscopies, in particular direct and inverse photoemission and soft x-ray emission, are well suited to derive a comprehensive view of the electronic structure (including the band gap) of candidate materials. However, as with all measurements, assumptions need to be made and pitfalls need to be avoided. Using GaInP2 and WO3 as model systems, experiments elucidating their electronic properties will be presented and discussed.

8822-25, Session 7

Soft x-ray spectroscopic study of mesoscale renewable energy materials *(Invited Paper)*

Jinghua Guo, Lawrence Berkeley National Lab. (United States)

Solar energy can be converted to electricity and chemical fuels for energy use and storage. However, the cost and conversion efficiency have been the biggest challenge for potential use of solar energy. There are the emerging technologies of using semiconductors for light harvesting assemblies; and charge transfer processes to solar cells. Controlling the crystallographic structure and the arrangement of atoms along the surface of novel materials will determine most of the physical and chemical properties.

Electronic structure ultimately determines the properties of matter. Soft x-rays address what the electrons are doing as they migrated between the atoms. Soft x-ray absorption spectroscopy (XAS) and emission spectroscopy (XES) have some unique features that are important to consider in regards to the element and atomic site selectivity and chemical state and symmetry sensitivity. The high-resolution selectively excitation has opened a new field of study by disclosing many new possibilities of soft x-ray resonant inelastic scattering (RIXS). In this presentation, some in-situ soft X-ray spectroscopy instrumentation development and recent studies of various solar energy conversion are presented. The results reveal the electronic structure of the 3d metal compounds in pure form and their variations upon doping. Also, in-situ characterization of photocatalysts demonstrated the way for real-time studies of chemical reactions.

8822-26, Session 8

Electronic transport and magnetic properties of graphene nanoribbons *(Invited Paper)*

Katsunori Wakabayashi, National Institute for Materials Science (Japan)

The electronic states of graphene near the Fermi energy are well described by massless Dirac Fermion [1]. The presence of edges, however, makes strong implications for the spectrum of the electrons [2][3]. In graphene nanoribbons with zigzag edges, localized states appear at the edge with energies close to the Fermi level. In contrast, edge states are absent for ribbons with armchair edges. Recently several reports appear on the synthesis of graphene nanoribbons using lithography techniques[4], chemical techniques[5].

In my talk, we focus on edge and nanoscale effect on the electronic properties of graphene nanoribbons. The electronic states of graphene nanoribbons strongly depend on the edge orientation. (A) In zigzag nanoribbons, for nonmagnetic long-ranged disorder, a single perfectly conducting channel emerges associated with a chiral mode due to the edge state, i.e., the absence of the localization in this class[6][7][8]. (B) We show the electronic transport properties of graphene nanojunctions crucially depend on the peripheral lattice structures[9]. The condition for electron confinement is discussed. We also show that the magnetic response of conductance peaks in the graphene nanojunctions depends on the configuration of nanojunctions. (C) Finally, we will discuss the effect of edge chemical modification on magnetic properties of nanographene systems[10]. Also, we discuss the hole doping effect on the spin-polarized states appearing along the graphene zigzag edges[11].

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8822-27, Session 8

Reversible hydrogen evolution and oxidation mediated by molecular ion

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Detailed steps of hydrogen generation/oxidation on the surface of polycrystalline platinum electrode are revealed based on analysis of mass and charge changes, thermodynamic, steric, and surface coverage arguments. Newly proposed intermediate - the molecular hydrogen ion - is shown to be essential mediator of the hydrogen evolution and oxidation reactions. The reversible character of the multi-step process is demonstrated. The entire electrochemical water reduction - hydrogen oxidation cycle has been explained on the molecular level and matches quantitatively with the most recent experimental and numerical results. These findings based on thermodynamic balance provides further insights in understanding and interpretation of hydrogen-related surface processes on Pt electrode and are expected to affect practical solutions relevant to water splitting, hydrogen generation, storage and development of fuel cells.

The presented analysis revisits the mechanism of reversible hydrogen evolution and oxidation reactions on Pt electrode and explains a thermodynamic contradiction related to participation of adsorbed hydrogen as intermediate in these processes, which has been unresolved for more than half a century. Novel mechanism makes it possible to account quantitatively for: (i) depolarization of hydrogen ion discharge from the theoretical standard potential value of –2.1 V to 0 V (vs. standard hydrogen electrode) and (ii) for mass changes on the electrode consistent with OH- ion release from the surface. By invoking molecular hydrogen ion as an intermediate in hydrogen evolution/oxidation on platinum, the quantitative agreement between the model and experimental data has been achieved and it is well supported by thermodynamic arguments.

8822-28, Session 8

Nanocrystal based hydrogen production with size-controlled cluster catalysts

Jochen Feldmann, Ludwig-Maximilians-Univ. München (Germany)

We report on hydrogen production with size-selected sub-nanometer cluster catalysts deposited on thin films of colloidal semiconductor nanocrystals. Pt clusters have been deposited under ultrahigh vacuum (UHV) conditions on CdS nanorods. For these UHV cluster decorated CdS nanorods we find higher hydrogen production rates than for CdS nanorods which have been cluster decorated via photodeposition.

The number of clusters per rod as well as the size of the Pt clusters have been varied [1]. Pt_{46} clusters show the best quantum efficiency as compared to smaller and bigger clusters. Quantum size effects are discussed to explain this non-monotonic behavior. We find in addition that below 40 Pt clusters per rod the quantum efficiency drastically drops, whereas the quantum efficiency saturates for higher cluster numbers.

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8822-29, Session 8

Nanowires from multi-crystalline Si for hydrogen generation

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Silicon nanowire arrays seems to be a promising architecture for solar energy conversion systems. By metal assisted chemical etching large areas of high quality nanowires can be produced on multi-crystalline silicon substrates. These areas show a low reflectance comparable to black silicon.

Here we studied multi-crystalline silicon nanowires for photoelectrochemical hydrogen generation. Nanowire array architecture provides good optical absorption along its axial direction, while facilitating collection of carriers radially. Because of the small diameter the limited minority diffusion length is no handicap.

A prototype cell showed enhanced open circuit voltage. However with increasing nanowire length lots of surface states were introduced leading to severe surface recombination. As a result the photocurrent is greatly reduced. Therefore the nanowire length should be well controlled.

The nanowire can greatly reduce the on-set potential for water splitting. The reason is that Si-H bond would attract electrons from inside of nanowire, leading to the enhanced p-type doping in nanowire.

8823-1, Session 1

Cu(In,Ga)Se2 semiconductor formation via the laser annealing of electrodeposited precursors

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Cu(In,Ga)Se2 is used as an absorber layer material for thin film photovoltaic devices with record power conversion efficiencies of >20%. In order to make such devices more economical, production costs need to be minimized. Electrodeposition of the absorber layer offers a low cost and resource efficient production route. However, the precursor film produced by this technique is a nanocrystalline, inhomogeneous material that requires thermal treatment to obtain good semiconductor properties. By combining electrodeposition with laser annealing we aim to investigate a possible high speed and economic production route.

Previously, we demonstrated that continuous wave laser annealing using a 1064 nm Nd:YAG laser at fluxes between 720 – 1080 Wcm-2 for one second improved crystallinity and optoelectronic properties of the electrodeposited material.

Here, we carry out a detailed structural characterisation of electrodeposited CuInSe2 and Cu(In,Ga)Se2 precursors annealed with this laser at fluxes of 50 and 945 Wcm-2. However, all films show the presence of secondary phases which will reduce device efficiency. In order to both improve the material and refine the annealing process, these phases must be identified. XPS and Raman analysis suggest the presence of a Cu-poor region at the surface. Additionally, grazing incidence XRD measurements evidence In-rich secondary phase(s) through the full depth of the absorber layer, for example CuIn3Se5 or In2Se3 which may stem from decomposition of CuInSe2. The presence of these phase(s) irrespective of precursor type and annealing conditions as well as past literature also suggests that this stems from the Cu-poor precursor composition.

8823-2, Session 1

CIGS thin film solar cell prepared by reactive co-sputtering

Jeha Kim, Cheongju Univ. (Korea, Republic of)

The reactive co-sputtering was developed as a new way of preparing high quality CuInGaSe2(CIGS) films from two sets of targets; Cu0.6Ga0.4 and Cu0.4In0.6 alloy and Cu and (In0.7Ga0.3)2Se3 compound targets. During sputtering, Cu, In, Ga metallic elements as well as the compound materials were reacted to form CIGS simultaneously in highly reactive elemental Se atmosphere generated by a thermal cracker. CIGS layer had been grown on Mo/soda-lime glass(SLG) at 500?C. For both sets of targets, we controlled the composition of CIGS thin film by changing the RF power for target components. All the films showed a preferential (112) orientation as observed from X-ray diffraction analysis. The composition ratios of CIGS were easily set to 0.71-0.95, 0.10-0.30 for Cu/[III] and Ga/[III], respectively. The grain size and the surface roughness of a CIGS film increased as the Cu/[III] ratios increased. The solar cells were fabricated using a standard base line process in the device structure of grid/ITO/i-ZnO/CdS/CIGS/Mo/ SLG. The best performance was obtained the performance of Voc = 0.45 V, Jsc =35.6, FF=.535, efficiency = 8.6% with a 0.9 ?m-CIGS solar cell from alloy targets while Voc = 0.54 V, Jsc =30.8, FF=.509, efficiency = 8.5% with a 0.8 ?m-CIGS solar cell from Cu and (In0.7Ga0.3)2Se3. In this paper, we report the growth and characterization of reactively co-sputtered CIGS thin films and the fabrication of solar cells.

8823-3, Session 1

How does the selenium activity influence CuInSe2 devices grown under Cu-excess?

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In spite of their better electronic properties, Cu-rich based CuInSe2 solar cells, limited by a high native doping which leads to tunneling enhanced recombination and shorter space charge region, performed worse than the Cu-poor ones. In order to decrease this doping, we investigate the effect of the selenium environment during the absorber growth, as it is known that changes in the selenium content of the material have dramatic consequences for the electronic structure. The selenium activity in the films was varied by either changing the selenium fluxes or by supplying different selenium species via our cracking system.

We demonstrate that the chemical activity of the selenium during the growth strongly influences both the film macrostructure and the solar cell performance. Firstly, X-Ray Diffraction measurements reveal that the texture of the absorbers is clearly affected by the selenium activity. Furthermore, all the solar cells characteristics improved, the efficiencies increasing from 4,3% to 8,6% with decreasing selenium activity. Intriguingly, this behavior is exactly the opposite of the Cu-poor ones.

We suspect that under low selenium activity, selenium vacancies are created which impact the doping of the Cu-rich material. A complete characterization of the defects levels via photoluminescence measurements on the films, admittance and capacitance-voltage measurements on the solar cells will be provided. We conclude that selenium deficiency enables reduction of the native doping of this material, which opens the way to benefit fully from the superior properties of this absorber for solar cell applications.

8823-4, Session 2

Spectrally and directionally selective intermediate reflectors for thin-film silicon tandem solar cells

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In thin-film silicon tandem solar cells, a hydrogenated amorphous silicon (a-Si:H) top cell and a hydrogenated microcrystalline silicon (µc-Si:H) bottom cell are connected in series. The two absorber layers are sensitive to high and low energy photons, respectively. The a-Si:H top cell is strongly affected by light-induced degradation, and a thin top cell is favorable. A spectrally and directionally selective intermediate reflector layer (IRL) eludes the opposing requirements to have a thin cell but a long optical path. The IRL between top and bottom cell is designed to reflect the light which can still be absorbed by the top cell, as well as having a sufficiently high electrical conductivity. Hydrogenated microcrystalline silicon oxide (µc-SiOx:H) is known to be a promising IRL material. By varying the oxygen content, refractive indices between 1.7 and 3 can be achieved. If properly designed, such an IRL reflects light back into the top cell. Yet, a poor spectral selectivity implies optical losses in the bottom cell caused by reflection side-lobes of the IRL in the long-wavelength range. We introduce a µc-SiOx:H-layer stack with alternating refractive indices. This spectrally and directionally selective IRL provides increased reflection in the desired spectral range while suppressing reflection in the long-wavelength range. As shown in wave-optical simulations for a flat layer stack, the reflection side-lobes are reduced leading to a 10% gain of short-circuit current density in the top cell accompanied by a severe reduction of losses of the bottom cell current of 22% compared

to the single layer IRL. First measurements, integrating the µc-SiOx:H layer stacks into thin-film silicon tandem solar cells, are presented and compared to the simulation.

8823-5, Session 2

Optical and electrical modeling of amorphous-silicon tandem solar cell with nonhomogeneous intrinsic layers

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A tandem solar cell made of amorphous-silicon alloys backed by a periodically corrugated metallic back-reflector was theoretically investigated. The absorptance for linearly polarized incident plane waves was computed using rigorous coupled-wave approach and the absorptance was used in Synopsys Sentaurus to compute the electrical properties of the solar cell. The intrinsic layers were taken to be nonhomogeneous in order to increase the probability of exciting multiple surface-plasmon-polariton (SPP) waves guided by the metal/semiconductor interface. The excitation of multiple SPP waves was identified by comparing the absorptance spectrums with the solution of the underlying canonical boundary-value problem. An AM1.5 solar irradiance spectrum was considered for computations.

8823-6, Session 2

A novel light trapping concept for liquid phase crystallized poly-Si thin-film solar cells on periodically nanoimprinted glass substrates

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Recent progress in the field of liquid phase crystallization (LPC) of silicon thin films on glass by e-beam yields high quality poly-Si, enabling a-Si:H/poly-Si heterojunction thin-film solar cells with record open circuit voltages up to 580 mV [1]. However, only moderate photocurrents (Jsc ≤20 mA/cm^2) have been achieved so far. Advanced light trapping concepts are therefore needed to fully exploit the efficiency potential provided by the high Voc level. By combining nanoimprint lithography with LPC, we developed a light trapping concept based on two-dimensional periodic scatterers, which is compatible with high temperature e-beam crystallization and industrial processing with respect to large area application and throughput: We imprint a square lattice pattern on Schott AF glass substrates using nanoimprint lithography and a high temperature-stable solgel resist. A boron doped 2-10 µm thick Si absorber is deposited in the nanocrystalline phase by high rate e-beam evaporation at a rate of 0.5 µm/min on the imprinted grating and subsequently liquid phase crystallized using a line-focused electron-beam source. Structural characterization of the textured absorber yields a high crystal quality (FWHM Raman TO phonon =3.4 cm^-1) and large grains (100-1000 µm) extending from the flat silicon-air interface down to the grating. We show that the surface grating leads to strong light trapping enhancing the absorption by more than a factor 3 in the near infrared, while the high electrical material qualitity known from planar layers is maintained. A detailed analysis of the influence of the surface grating on the respective solar cell parameters will be presented.

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8823-7, Session 3

Study of the effect of the charge transport layer in the electrical characteristics of the organic photovoltaics

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Significant progress in fabrication and optimization of organic photovoltaics (OPVs) has been made during the last decade. The main reason for popularity of OPVs is due to their low production cost, large area devices and compatibility with flexible substrates. Various approaches including optimizing morphology of the active layers, introducing new materials as the donor and acceptor, new device structures such as tandem structure have been adapted to improve the efficiency of the organic photovoltaics. However, electrical characteristics of the OPVs do not only depend on the active layer materials or device structure. They can also be defined by the interface properties between active layers and the charge transport layers or the metal contacts. Within this paper, the effect of the thickness variation of the charge transport layer in the electrical properties of the bilayer heterojunction OPVs has been studied. Several devices with CuPc/PTCDI-C8 as the donor/acceptor layers have been fabricated with different thicknesses of electron transport layer. MoO3 and Alq3 have been used respectively as the hole transport layer (HTL) and the electron transport layer (ETL). It has been shown that the S-shape effect in the current–voltage curve is attributed to the accumulation of the charge carriers at the interface between the active layer and the charge transport layer.

8823-8, Session 3

QCM-D characterization of dye adsorption in TiO2

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Understanding dye adsorption and desorption to TiO2 is crucial for designing dye-sensitized solar cells (DSSCs) with enhanced efficiency. Maximizing dye adsorption to the TiO2 semiconductor increases efficiency by increasing the probability of charge transfer to the electrode. Understanding the kinetics of dye adsorption is useful for determining the optimal adsorption time and dye concentration that results in the highest dye loading. The dye monolayer also improves efficiency by acting as a blocking layer to prevent electron recombination from the semiconductor to the liquid electrolyte. One methodology that is used in studying recombination rate is a homogeneous partial coverage dye layer. There has been debate over the effectiveness of certain procedures of combined adsorption and desorption for creating a homogeneous partial coverage layer. A better understanding of the kinetics of desorption has applications in creating optimal partial coverage layers for research. QCM-D provides adsorption measurements in real time and therefore allows one to determine the kinetics of the process. Others have recently demonstrated the applications of QCM-D to show in-situ dye adsorption on flat TiO2 surfaces (Harms et al. 2012). In this work, we characterize the adsorption and desorption of a ruthenium-based dye using a TiO2-coated sensor to simulate the TiO2 substrate of a DSSC. We further propose a model to relate dye adsorption in mesoporous TiO2 and QCM frequency shift for further study.

8823-9, Session 3

Effects of surfactants on agarose-based magnetic polymer electrolyte for dye-sensitized solar cells

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A new type of magnetic polymer electrolytes is designed for solid-state dye-sensitized solar cell (DSSC) applications with agarose as the polymer matrix and Fe3O4 nanoparticles as the magnetic filler. The magnetic properties of the Fe3O4 nanoparticles is anticipated to prompt the formation of aligned polymer chains in the electrolytes after the application of an external magnetic field, which can improve their ionic conductivity and interfacial contact with the TiO2 porous film. However, due to the small grain size and high surface energy of the Fe3O4 nanoparticles, they are easy to aggregate, which limits the homodispersity of the nanoparticles and hinders the ionic transport in the electrolytes. In this work we utilized four different surfactants, i.e., sodium dodecyl sulfate, polyvinylpyrrolidone, polyethylene glycol (PEG200), and polysorbate 80 (TW-80), to modify the surface properties of the Fe3O4 nanoparticles in order to improve their distribution in the electrolytes and enhance the DSSC performance. TW-80 and PEG200-modified Fe3O4 nanoparticles were found to exhibit improved dispersion properties according to surface morphology characterizations of the electrolytes containing these nanoparticles. Electrochemical impedance spectroscopy measurements revealed improved ionic conductivity in the electrolytes and electron lifetime in the solid-state DSSCs, with TW-80 modified electrolyte achieving the highest ionic conductivity of 2.98 ? 10?3 S/cm. In addition, the DSSCs' performance was also enhanced due to the surfactant modification of the Fe3O4 nanoparticles, and the energy conversion efficiency was increased from 0.8% for the original cell to 1.83% for the cell that had the electrolyte with TW-80 modified Fe3O4 nanoparticles.

8823-10, Session 4

Enhanced light absorption in thin-film solar cells with light propagation direction conversion

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Enhancement of optical absorption in thin-film solar cells (TF-SCs) has been the long-lasting issue to achieve high efficiencies. Key issues for the photon management in TF-SCs are divided into two categories. One is antireflection of light incident on TF-SCs, and the other is trapping of incident light in TF-SCs. Trapping of incident light has been actively studied employing diffraction gratings. Grating couplers (GC) have been actively studied as a method to trap incident light. GCs convert incident light into guided modes propagating along TF-SCs to extend optical path for higher optical absorption. However the wavelength band for the efficient conversion remained relatively narrow and the overall improvement of TF-SC efficiencies has been limited. This paper demonstrates that the grating height design as well as the phase matching condition is important for the enhancement of optical absorption in TF-SCs. Especially we show that the grating height that gives periodic lateral π-phase shift to the normal incident light gives the key factor to enhance the optical absorption. We demonstrate it with the calculation of short-circuit currents as a figure of merit for optimization. The influence of the light absorption coefficients and grating coupling strengths on the light absorption bandwidth is also discussed.

8823-11, Session 4

Natural evolution inspired design of light trapping structure for thin film organic solar cells

Chen Wang, Shuangcheng Yu, Wei Chen, Cheng Sun, Northwestern Univ. (United States)

Light trapping has been developed to effectively enhance the efficiency of the thin film solar cell by extending the path-length for light interacting with the active materials. Searching for optimal light trapping design requires a delicate balance among all the competing physical processes, including light refraction, reflection, and absorption. The existing design methods mainly depend on engineers' intuition to predefine the topology of the light-trapping structure, because the underlying nonlinear process often hinders the formulation of inverse design problem. However, these methods are not capable of handling the topological variation in reaching the optimal design. In this work, a systematic approach based on Genetic Algorithm is introduced to design the scattering pattern for effective light trapping. Inspired by natural evolution, this method can gradually improve the performance of light trapping structure through iterative procedures, producing the most favorable structure with minimized reflection and substantial enhancement in light absorption. A realistic organic thin film solar cell consists of a 200nm ITO front transparent electrode, a 30nm P3HT:PCBM active layer and a metallic back electrode. The scattering layer consisting of nano-scale patterned front layer is optimized to maximize absorption by strongly coupling incident sun light into the localized photonic modes supported by the multilayer system. Rigorous coupled wave analysis (RCWA) is implemented to evaluate the absorbance. Nearly 50% average absorbance over the solar spectrum is obtained for the optimized scattering pattern, with short circuit current density five times larger than the control case using planar ITO layer.

8823-12, Session 4

Submicron texturing for broadband light management in thin-film PV

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Developing appropriate light management schemes is one of the challenges in high-efficiency thin-film solar cells research, including minimizing reflection between layers and maximizing the optical path length in the absorbing layers. Traditional approaches are based on anti-reflection coatings (ARCs) and surface texturing. The latter is preferred due to its operation over a wider spectrum and its light scattering capability.

In this work we explore different submicron-scale periodic surface texturing morphologies through finite-difference time-domain (FDTD) computations. The broadband reflection response is studied at air/silica and silica/TO (Tin Oxide) interfaces, within a spectral range of 300-2500 nm. A Drude-Lorentz model is used to account for material dispersion and absorption within the wavelengths of interest. In order to optimize the light trapping performance, two-dimensional transmission and reflection simulations of the surface textures are compared with those of flat interfaces. Numerical results demonstrate a reduction in reflection for the air/silica interface to values below 1%, compared to up to 4% for the non-textured interface. For the silica/TO interface, reflection decreases to less than half when compared to the non-textured interface. Further structures that replicate perfect multiple-layer anti-reflection coatings are also studied. These structures are tuned to cancel specific wavelengths and can create an arbitrary effective index, overcoming the constraint of available discrete refractive indices. The best texturing results obtained for the air/silica and silica/TO interfaces are combined in one stacked structure, achieving reflection values about one order of magnitude below, when compared to a non-textured air/silica/TO stack.

8823-13, Session 5

Reactive sputtering of amorphous In-Zn-O TCO from metallic targets

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Amorphous In-Zn-O (a-IZO) transparent conducting oxides with conductivity ? ≈ 3000 S/cm can be sputter deposited at ambient temperature, are damp heat resistant and have been demonstrated to work well at transparent contacts for CIGS PV and Epi-Si PV. However, the high cost of ceramic In-Zn-O sputter targets has limited the widespread use of a-IZO TCOs in PV. Here, we demonstrate a new process that results in conductive and transparent a-InZnO thin films deposited via reactive sputtering from a metallic In-Zn alloy target. The highest conductivity obtained to date, ? ≈ 2100 S/cm, is an order of magnitude higher than the previous best literature result for reactively sputtered a-InZnO.

A series of 70 nm thick a-In-Zn-O thin films were grown on 2”x2” Eagle 2000 glass substrates by sputtering from a 3” diameter 87:13 In:Zn wt. % metal alloy target. We have found through a series of RF, DC and RF superimposed DC deposition techniques that DC sputtering produced the best results. Through careful control of target power density and incorporation of a high throughput cathode cooling circulator, we were able to avoid any melting of the high indium content target. The total deposition pressure was 2.5 mTorr from a 20 sccm total gas flow with approximately a 4:1 Argon-O2 flow ratio. First, in order to obtain the reproducible results necessary to enable reproducible experimental control the conductivity and transparency, it was necessary to obtain a stable surface composition on the metallic-target by pre-sputtering before deposition. Through control of process gas composition, the thin film transparency and conductivity could be varied from dark grey and metallic (<80% transmissive) (too little oxygen); to clear (>90% transmissive) and conducting (~16 – 18 % O2 in Ar); to clear/yellow (>90% transmissive) and low conductivity (too much oxygen). The best samples had ? ≥ 2000 S/cm with 90 % transparency. The X-ray diffraction measurements show the films to be amorphous. We will discuss how that it is essential to realize how and why that in order to optimize the conductivity of a-InZnO thin films careful Indium-content-specific control of the oxygen content within the sputter gas mix is required.

8823-15, Session 5

Electrical properties of point defects in CdS from first principles

Joel B. Varley, Vincenzo Lordi, Lawrence Livermore National Lab. (United States)

One of the most significant sources of efficiency loss in manufactured thin-film solar cells is absorption by the buffer layer without contributing useful photocurrent. The most common buffer layer material is cadmium sulfide (CdS), which exhibits very good electrical properties, but whose band gap (2.4 eV) is too small to be transparent to the entire solar spectrum. The use of a wider band gap material with good electrical properties is desired, but the precise material characteristics dictating the electrical properties are not fully understood. Here we present a first principles study of the thermodynamic and electrical characteristics of intrinsic (vacancy, interstitial, antisite) and common extrinsic (O, OH, Na, C, N) point defects in CdS, to serve as a reference. We use density functional theory to calculate the structures, formation energies, and energy levels the defects, from which we analyze the electrical nature, carrier compensation, and carrier recombination properties of the defects, in the context of buffer layer electrical properties in a thin-film solar cell. Correlation of defect properties with growth conditions is made in terms of film stoichiometry and presence of impurities. Prepared by LLNL under Contract DE-AC52-07NA27344; supported by the DOE EERE SunShot/BRIDGE program.

8823-17, Session 6

Characterization of printed CZTSSe films for photovoltaic applications

Wei Wu, Yanyan Cao, Jonathan V. Caspar, Qijie Guo, Lynda K. Johnson, Irina Malajovich, H. David Rosenfeld, Kaushik Roy Choudhury, Lee Silverman, DuPont (United States)

Cu2ZnSn(S,Se)4 (CZTSSe) is a promising alternative absorber material for thin-film photovoltaic applications because of its earth-abundant and non-toxic constituents, tunable band gap, and high optical absorption coefficient. Recently, we have reported a high efficiency (8.5% conversion efficiency) PV (photovoltaic) device employing CZTSSe thin film prepared by solution based chemical method (Cao et al, J. Am. Chem. Soc., 2012, 134 (38), 15644), which offers the exciting prospect of low-cost scalable processing routes to solar cells. In this talk, we will present more detail on the electrical characterization of these printed CZTSSe films. We will combine the experimental optoelectronic properties of the CZTSSe films and their corresponding PV devices to develop numerical models for the CZTSSe devices. We will compare the model results with real devices and discuss possible efficiency loss mechanisms and potential paths for device improvement.

8823-18, Session 6

Fabrication of Cu2ZnSnSe4 solar cells by liquid-phase pulsed laser ablation (LP-PLA) and electrophoretic deposition (EPD)

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Previously, we have successfully developed a non-vacuum and environmental-friendly technique for fabrication of Cu(In,Ga)Se2 thin film solar cells using liquid-phase pulsed laser ablation (LP-PLA) and electrophoretic deposition (EPD). In this report, we extend this approach for fabrication of Cu2ZnSnSe4 (CZTSe) absorber layers, and achieve 4.77% power conversion efficiency for lab-scale CZTSe solar cells.

First, colloidal metallic nanoparticles of Cu-Zn-Sn (CZT) alloys are produced by pulsed laser ablation of a bulk alloy target in common organic solvents. Without addition of stabilizing ligands, the nanoparticles are found to be electrostatically stabilized against agglomeration. Without transferring to another solvent and without using additional binders, precursor CZT films are rapidly deposited on Molybdenum sheet substrates using two-electrode electrophoretic deposition in the as-made colloids. Highly pure and compact CZT thin films are obtained after optimization of the deposition parameters. Finally, the precursor CZT films are selenized in Se vapor to form well-crystallized CZTSe absorber layers, and solar cells are finished with standard procedures. Energy conversion efficiency up to 4.77% is measured for such cells fabricated on Molybdenum sheet substrates with VOC=0.32 V, JSC=34.7 mA/cm2, and fill factor=43.5%. XRD, SEM-EDS, and Raman spectroscopy are provided to characterize film structure, composition, and impurities. High resolution transmission electron microscopy (HRTEM) is also performed to study the colloidal nanoparticles’ microstructure and extended defects (e.g. grain boundaries) in the CZTSe absorber layers.

Particular advantages of the LP-PLA/EPD approach include high deposition rate (?m/min), nearly zero chemical waste, and compliance with streamline-based coating on flexible substrates or complex surfaces.

8823-19, Session 6

Synthesis of colloidal Cu2ZnSnS4 nanocrystals with different compositions and sizes for solar cell applications

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There have been intensive efforts to use semiconductor nanocrystals(NCs) for solar cells with low cost and high efficiency. It has been reported that solar cells using photo absorber layers based on nanocrystals such as PbSe, CdTe, Cu(In1-x,Gax)Se, etc. shows efficiencies ranging of 1-5%. However, these materials are not preferable for practical application due to the cost and scarcity problems of Cd, In, Ga. Thus, one major challenge for thin film solar cells based on NCs is develop materials composed of earth abundant and nontoxic elements.

Cu2ZnSnS4 (CZTS) is composed of earth abundant, nontoxic elements, and has feature suitable for solar cells, including a direct band gap of ~1.5 eV ,and large absorption coefficient of ~1?104 cm-1. There have been efforts to synthesis CZTS nanocrystals and to use it for solar cells, but the device performance remains relatively low. In addition, the device fabrication process and device performance have not yet been well studied. In this study, we attempted to develop a feasible way for making CZTS thin film for solar cell applications. We also studied the effects of composition and sizes of CZTS nanocrystals on the performance solarcell made with a CZTS nanocrystal ink.

CZTS NCs were synthesized by heating metal acetylacetonates and elemental sulfur in Oleylamine at 220 C .their compositions was controlled by changing starting precursor compositions. Heterojunction having a structure ITO/ZnO/CdS/CZTS NCs/ Au were fabricated by wet processes. They showed photovoltaic effects, largely depending on the composition of CZTS nanocrystals.

8823-20, Session 6

A two-step synthesis of earth-abundant solar cell material, CZTS by co-sputtering and sulfurization

Nadarajah Muhunthan, Om Pal Singh, Nita Dilawar, Rashmi Rashmi, Keadr Nath Sood, Vidya Nand Singh, National Physical Lab. (India)

For the fabrication of low cost and sustainable thin film solar cells, it is essential that it should be made from earth abundant materials. Copper zinc tin sulfide (CZTS) is such a material. In the present study, CZTS thin films have been synthesized using co-sputtering and sulfurization. The co-sputtering was carried out by sputtering three metallic targets (Cu, Zn and Sn) simultaneously. Cu was sputtered using DC power; Zn and Sn were sputtered using RF power. The grown films were 800 nm -1000 nm thick. The deposition rate was 7- 10 nm/min. The sulfurization was carried out in a horizontal tube furnace using H2S diluted with argon (H2S-15% and Ar-85%) with a flow rate of 12.5 sccm. The furnace temperature was increased to 400oC in 10 min. Then, the temperature was increased from 400oC to 550oC in another 10 min and was kept at 550oC for 25 min. Finally, furnace was cooled down to room temperature. The films were characterized for its structural, optical and electrical properties. Grazing incidence XRD analysis showed that sulfurized films were having phase pure CZTS (kesterite structure) with orientation along (112) plane. Raman peak at 336 cm-1 confirmed the kesterite structure of CZTS films. The energy dispersive x-ray spectroscopic (EDS) analysis showed that the film consisted of Cu, Zn, Sn and S only; no other elements were detected in EDS analysis. SEM analysis showed a homogeneous, compact surface morphology and large columnar grains throughout the surface of the film. The CZTS films were having optical absorption coefficient higher than 104 cm-1 and an optical band gap of 1.50 eV was estimated using the Tauc's plot. The resistivity and activation energy of the CZTS film are 6.4 ?cm and 16 meV, respectively. The optical and electrical properties show that films are suitable for thin film solar cell applications.

8823-21, Session 6

Fabrication and analysis of high-efficiency CdTe thin-film solar cells *(Invited Paper)*

Yanfa Yan, Naba Paudel, The Univ. of Toledo (United States); Jonathan D. Poplawsky, Chen Li, Stephen J. Pennycook, Oak Ridge National Lab. (United States); John Moseley, Helio R. Moutinho, Mowafak M. Al-Jassim, National Renewable Energy Lab. (United States)

We report on our recent progress on the fabrication and analysis of high-efficiency CdS/CdTe thin-film solar cells. High-efficiency CdTe thin-film solar cells were fabricated on commercial SnO2:F-coated soda-lime glass substrates. The CdTe absorbers were deposited by close-spaced sublimation. The best small-area cell has shown an efficiency of 15.5% with an open-circuit voltage of 844 mV, a short-circuit current of 24.0 mA/cm2 and a fill-factor of 76.6% measured under an AM1.5 illumination. The cells were systematically characterized by current-voltage (J-V) and quantum efficiency (QE) measurement and electron-based techniques such as electron-beam induced current (EBIC), cathodoluminescence (CL), electron back scattered diffraction (EBSD), electron energy loss spectroscopy (EELS), and imaging. The characterization and analysis provided critical understanding on how the high-efficiency cells are achieved. We find that high-efficiency solar cells exhibit the following characteristics: (1) Grain boundaries are well passivated by Cl during the CdCl2 heat treatment, (2) CdTe/CdS junctions are optimized by incorporating O in CdS, (3) The back contacts must have resistance. In this presentation, we will review the device processes applied to realize these characteristics and characterization results obtained from high-efficiency CdTe thin-film solar cells.

8823-22, Session 6

Solution-processed CdTe/ZnO nanocrystal solar cells

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This paper describes the fabrication of thin film solar cells based on nanocrystal inks of CdTe. We demonstrate that totally solution processable solar cells can be fabricated in air at temperatures as low as 300 °C. Focusing on a CdTe/ZnO thin-film system, we report solar cells that achieve power conversion efficiencies of upto 10% with greater than 90% internal quantum efficiency. In our approach, nanocrystals are deposited from solution in a layer-by-layer process. Chemical and thermal treatments between layers induce large scale grain formation, turning the 4 nm CdTe particles into pinhole-free films with an optimized average crystallite size of ?70 nm. Through capacitance-voltage measurements we demonstrate that the CdTe layer is fully depleted which enables the charge carrier collection to be maximized. We will also discuss in detail the processing conditions that can be used to optimise these devices. We show that the extent of grain growth achieved during the CdTe sintering process is strongly dependent on the nanocrystal surface chemistry, with removal of the organic capping ligands prior to annealing leading to greatly enhanced growth. The overall performance of these solar cells is shown to be strongly dependent on both annealing temperature and time, with optimal results requiring a balance between crystal growth and degradation.

8823-23, Session 6

4-terminal tandem photovoltaics with organic top cells on CIGS bottom cells

Zach M. Beiley, Mark G. Christoforo, Andrea R. Bowring, Stanford Univ. (United States); Paul Gratia, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Michael D. McGehee, Stanford Univ. (United States)

It is estimated that for photovoltaics to reach grid parity around the planet, they must be made with costs under $0.50 /Wp, and in order to keep installation costs down, must also achieve power conversion efficiencies above 20%. Recently we proposed a novel solar cell architecture, a hybrid tandem photovoltaic (HTPV), in which the top cell is an emerging photovoltaic technology that can be deposited at low temperatures and with rapid throughput, such as an organic or dye-sensitized cell, and the bottom cell is one of a variety of traditional inorganic photovoltaics, such as silicon or CIGS. Our efforts in modeling have already demonstrated that it should be possible to add an organic photovoltaic on top of moderately efficient silicon and CIGS bottom cells to improve their efficiencies to over 20%. In this work, we demonstrate a prototype HTPV device, which consists of an organic photovoltaic that is mechanically stacked on a CIGS bottom cell. In this architecture, the top and the bottom cells each have their own electrodes, which removes the current matching constraint of traditional tandem cells and allows for the independent optimization of the subcells. To make high performing organic top cells with two transparent electrodes, we use meshes of silver nanowires embedded in a less conductive material to fill the gaps in the mesh. We present our strategy for fabricating these electrodes and discuss the developments in organic photovoltaic technology that will be necessary to push HTPV efficiencies above 20%.

8823-25, Session PMon

Comparison of CIGS thin films prepared by sequential HiPIMS or DC magnetron sputtering and selenization process

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Cu(In,Ga)Se2 (CIGS) thin films were prepared by two-step process using DC or High Power Impulse Magnetron Sputtering (HiPIMS) of metallic precursors followed by selenization in Se or Ar+Se atmosphere. Single composite target (2”) with stoichiometry Cu0.45In0.40Ga0.15 was used for sputtering of metallic precursors. Repetition frequency of HiPIMS excitation was 100 Hz (T=10 ms) and active pulse duration 100 µs (duty cycle 1%). Maximum peak current was 18 A. Average absorbed power, cathode voltage and discharge current was in HiPIMS and DC plasma the same. Some plasma parameters were analyzed by Optical Emission Spectroscopy (OES), voltage and current waveforms were monitored by digital oscilloscope. Properties of resulting CIGS films were measured by X-ray diffraction (XRD), Raman spectroscopy, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX) and some electrical characteristics were measured by Van der Pauw method. The basic aim of this work is to compare main properties of final layers depending on magnetron excitation mode and thermal treatment. All the CIGS films revealed chalcopyrite crystal structure with preferential (112) orientation, perfect stoichiometric composition and average resistivity about 0.15 ?•cm. Only very small influence of magnetron excitation mode on thin films properties was observed. On the other side selenization in Ar+Se atmosphere led to bigger grain size, smoother surface, better crystallinity and significantly higher level of Ga substitution.

8823-26, Session PMon

Plasmonic nanodot array optimization on organic thin film solar cells using anodic aluminum oxide templates

Kyuyoung Bae, Kyoungsik Kim, Yonsei Univ. (Korea, Republic of)

The fabrication method of plasmonic nanodots on ITO substrate has been developed to improve the efficiency of organic thin film solar cells. Metallic nanodot array on ITO substrate shows a Surface Plasmon Resonance in optical wavelength region and the Surface Plasmon Resonance helps the improvement of absorption in photovoltaic materials. Nanoscale metallic nanodots arrays are fabricated by anodic aluminum oxide (AAO) template mask which can have different structural parameters by varying anodization conditions. Structural parameters such as periodicity, radius and height of the metallic nanodots are controlled by anodizing voltage and pore widening time of AAO, and deposition time of metal. In this letter, the structural parameters of metallic nanodots, which can be controlled by the diverse structures of AAO template mask, are investigated to enhance the optical properties of organic thin film solar cells. It is found that optical properties of the organic thin film solar cells are clearly improved by finding optimization values of the structural parameters of the metallic nanodots array.

8823-27, Session PMon

Study of the chemical composition and structural properties of the CZTSe thin films

Anatoliy S. Opanasyuk, Sumy State Univ. (Ukraine); Hyeonsik Cheong, Sogang Univ. (Korea, Republic of); Aleksey E. Bolotnikov, Brookhaven National Lab. (United States); Pavel Koval, Sumy State Univ. (Ukraine); Ralph B. James, Brookhaven National Lab. (United States)

The Cu2ZnSnSe4 (CZTS?) thin films attract great attention as a new abundant and nontoxic material for photovoltaic technology instead conventional CIS, CIGS and CdTe compounds.

The CZTS? thin films were obtained by the co-evaporation of the components on the Mo coated glass substrate. The structural properties of the samples were studied by the X-ray diffraction method. In order to study chemical composition of the thin films the proton induced X-ray emission (PIXE) method was used. The ?-PIXE setup consists of proton accelerator complex “Sokol” (Institute of Applied Physics, Sumy, Ukraine) which provide formation of the proton beam proton beam with the energy of 1.5 eV and microprobe channel allowing to focus proton beam on the sample surface (spot size of about 9?6 µm). The scanning area was 200?200 µm. The chemical composition was tested for the two randomly selected points on a surface.

The X-ray analysis of the thin films revealed practically single phase tetragonal structure with the growth texture along [211]. The lattice parameters are varied in the following ranges a=(0.56640-0.56867) nm, ?=(1.13466-1.13776) nm (?/2a = 0.9983-1.0017).

As a result of a PIXE analysis the influence of the growth conditions on the samples chemical composition was determined, as well as surface distribution map.

8823-28, Session PMon

Structural and substructural features of chemically deposited zinc oxide thin films

Taisia Berestok, Anatoliy S. Opanasyuk, Sumy State Univ. (Ukraine); Aleksey E. Bolotnikov, Ralph B. James, Brookhaven National Lab. (United States); Petro M. Fochuk, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

Due to its low toxicity, Cd-free, large band-gap (Eg=3.37 eV) zinc oxide is an effective absorber of ultraviolet radiation and perspective material for use as conductive and optical cover layers of large-area solar cells. There are many methods of obtaining ZnO thin films. But recently much attention has been attracted to fabrication of this material by chemical methods because of their efficient, cost-effective and large-scale capability.

The deposition of ZnO thin films was carried out by chemical bath deposition from a zinc nitrate and hexamethylene tetramine solution. The temperature of the initial solution was 368 K. The duration of the deposition was varied in the range from 60 min to 180 min. Structural and sub-structural investigations were carried out using high-resolution scanning electron microscopy and X-ray diffraction method.

These experiments enabled us to study features of the films' structure formation and to determine basic structural characteristics (phase analysis, texture quality, lattice constants, grain size, coherent scattering domain size (CSD), and concentration of dislocations). It is shown that the films have a hexagonal structure ZnO with lattice constants of a=0.33895 and c=0.51446 nm and growth texture [100]. The values of CSD were equal to L(100) = (40-82) nm and L(101) = (30-70) nm. Regimes of the deposition of the films with optimal structural characteristic for use in the solar-energy industry were found.

8823-29, Session PMon

THIN MULTI JUNCTION SOLAR CELLS OF III-V MATERIALS TO ADVANCE SOLAR ENERGY HARVESTING

Stefania A. Castelletto, Albert Parker, RMIT Univ. (Australia)

Thin film silicon solar cells have very low collection efficiency. Surface nanostructures may significantly improve this efficiency working on the light trapping and the conversion of the light in electron flow. The most promising solutions mimic nature in the shape of the nanostructure above the silicon layer and/or use the properties of other semiconductor of better than silicon performances. Results of finite difference time domain simulations obtained with the new Lumerical software are presented in details for the composite thin film solar cells with the proposed surface textures.

8823-31, Session PMon

Characterization of semiconductor materials with lifetimes from ns to ms using time-correlated single photon counting

Volker Buschmann, Felix Koberling, Peter Kapusta, Uwe Ortmann, Tino Roehlicke, Michael Wahl, PicoQuant GmbH (Germany); Hannes Hempel, Christian Kraft, Friedrich-Schiller-Univ. Jena (Germany); Maurizio Roczen, Bernd Rech, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Rainer Erdmann, PicoQuant GmbH (Germany)

The luminescence lifetime of semiconductor materials can vary over a broad range from microseconds to milliseconds for indirect semiconductors like Si down to sub-nanoseconds for III/V and II/VI based thin film or organic materials. The lifetime of a given wafer sample depends on the free charge carrier dynamics and therefore strongly on the sample preparation. An important example is the influence of bulk or surface defects [1], thus the luminescence lifetime is a possible indicator for wafer quality. Luminescence of individual layers can be addressed by spectral means [2].

We have modified a recently developed setup for time-resolved photoluminescence measurements (TRPL) based on pulsed diode lasers and time-correlated single photon counting with highly sensitive single photon detectors to study the luminescence lifetime dependence of polycrystalline CdTe on activation and deposition conditions by time and spatially-resolved photoluminescence measurements.

TRPL measurements on indirect semiconductors require only a relatively low time resolution, but short dead times of the photon counting electronics are beneficial to avoid long acquisition times and dead-time induced artifacts. To address this time-range, a new photon counting unit with only a few nanoseconds dead time was integrated into the TRPL-mapping system and used to monitor the luminescence of silicon nanodots.

1) D.A. Bender et al., Proc. SPIE, Vol. 6461 646109 (2007)

2) V. Buschmann et al., Proc. SPIE, Vol. 8460 84700F (2012)

8823-32, Session PMon

Structural and interfacial properties of large area n- a-Si:H/i-a-Si:H/p-c-Si heterojunction solar cells

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Large area (72 cm2) doping inversed HIT solar cells (n-a-Si:H/i-a-Si:H/p-c-Si) were investigated by High Resolution Transmission Electron Microscopy (HR-TEM), Spectroscopic Ellipsometry (SE), Fourier Transform Infrared Attenuated Total Reflection spectroscopy (FTIR-ATR) and current-voltage (I-V) measurement. Mixture of microcrystalline and amorphous phase was identified via HR-TEM picture at the interface of i-a-Si:H/p-c-Si heterojunction. Using multilayer and Effective Medium Approximation (EMA) to the SE data, excellent fit was obtained, describing the evolution of microstructure of a-Si:H deposited at 225 °C on p-c-Si. Cody energy gap with combination of FTIR-ATR analyses were consistent with HRTEM and SE results in terms of mixture of microcrystalline and amorphous phase. Presence of such hetero-interface resulted poor open circuit voltage, Voc, of the fabricated solar cell devices, determined by I-V measurement under 1 sun. Moreover, Voc was also obtained from dark I-V analysis, revealing consistent Voc values. Efficiency of fabricated cells over complete c-Si wafer (72 cm2) was calculated as 4.7 and 9.2 %. Improvement in efficiency was interpreted due to the back surface cleaning and selecting aluminum/silver alloy as front contact.

8823-33, Session PMon

Surface photovoltage as a tool to monitor the effect of hydrogen treatment on a-Si:H/c-Si heterojunction

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The tendency on shrinking the mono crystalline silicon wafer thickness lower than 100 ?m is delivering the use of low temperature processes to avoid thermal stress and wafer bowing. This issues can be faced with amorphous/crystalline (a-Si:H/c-Si) silicon heterostructure in which the thin a-Si:H layers are deposited by Plasma Enhanced Chemical Vapour Deposition (PECVD) system at temperature below 300°C. Nevertheless this technology has already demonstrated its potentiality leading to high efficiency solar cell device, investigation are still running concerning the c-Si surface conditioning, amorphous materials and hydrogen plasma treatments to improve the interface quality. In this framework we propose the use of Surface Photovoltage (SPV) technique to evaluate the density of state at the heterointerface that is the most relevant issue to be controlled to achieve high performance solar cell. The SPV technique is utilized as contact-less measurement tool of the energetic distribution of the interface state density surface that imposes a band-bending at the heterointerface. The band-banding can be modulated by an external bias voltage establishing a correlation between silicon substrate preparation, resulting charge, density and energetic distribution of rechargeable interface states. In this work, after a brief description of the SPV technique adopted, the effect of hydrogen treatments performed before and/or after amorphous silicon deposition is evaluated. Defect density at the a-Si:H/c-Si heterointerface and SPV transient phenomena related to both surface recombination and crystalline silicon bulk lifetime are presented and detailed discussed to establish the effectiveness of hydrogen plasma treatments to improve the solar cell performances.

Sunday - Tuesday 25–27 August 2013

Part of Proceedings of SPIE Vol. 8824 Next Generation (Nano) Photonic and Cell Technologies for Solar Energy Conversion IV

8824-1, Session 1

Towards low cost full spectrum photovoltaic systems: choice of materials, devices, system designs, and integrated manufacturing processes *(Invited Paper)*

Partha S. Dutta, Rensselaer Polytechnic Institute (United States)

The efficiency of silicon based single junction photovoltaic (PV) technology is reaching its theoretical limit of around 25% and the cost of large area panels is rapidly declining world-wide. Hence research for any future PV technologies must be focused in the direction of developing higher efficiency systems at low cost to successfully compete with alternative energy generation technologies. At the same time, using earth abundant materials and systems that could be easily recycled after it usable operating lifetime must be considered for sustainability. For developing high efficiency systems, pathways to convert the entire solar spectrum using tandem or stacked solar cells with different bandgaps are well known for decades. Space grade tandem solar cells are known to provide conversion efficiencies close to 40%, but at economies that are not feasible for terrestrial deployments. This talk will present a suite of research topics in the areas of nano- and micro scale materials synthesis, simple device designs and methodologies to integrate materials and devices into PV systems using low cost processing technologies. In particular, progress made in the areas of (a) layered semiconducting compounds that enables large area exfoliation and ease of metal contacts for effective charge transport (compared to other form factors of nano-scale materials), (b) edge illuminated devices avoiding grid shadowing effects and (c) mechanically stacked multiple bandgap devices will be presented.

8824-2, Session 1

Ultra-high efficiency compact solar modules enabled by photonic superprisms *(Invited Paper)*

Peter Bermel, Purdue Univ. (United States)

There is currently a great demand for portable, flexible solar systems offering efficiencies exceeding the Shockley-Queisser limit of 31% for unconcentrated sunlight. In this work, we present a novel approach to designing 1” diameter self-contained modules utilizing self-assembled photonic crystal superprisms for high-performance spectral splitting and light trapping by multiple distinct bandgap PV materials. Advantages of this approach include high spectral splitting performance, wide solar acceptance angles, metallic nanostructures for improved heat sinking, low material deposition costs, and amenability to large-scale manufacturing utilizing self-assembly and flip-chip integration.

8824-3, Session 1

High efficiency solar spectrum splitting using multilayer chirped high-contrast subwavelength grating

Yuhan Yao, He Liu, Wei Wu, The Univ. of Southern California (United States)

In order to harvest solar energy with efficiency beyond the state-of-the-art solar cells, spectrum splitting schemes were proposed. However, most of those systems are based on bulky geometrical optical elements and expensive optical filters, and require drastic change from convention photovoltaic setup.

We invented a new spectrum splitting system. The key element in the invention is a high-efficiency planar dispersive mirror, which will be used to replace the mirror in a solar concentrator. The dispersive mirror is based on multilayer of chirped sub-wavelength high-contrast dielectric gratings (HCGs). The sunlight will be reflected dispersively to each cell, which are arranged in parallel, according to the wavelength. Lights with short wavelength are reflected dispersively by the top HCG layer, and longer wavelengths go through top layers and are reflected by lower layers to different angles.The properly chirped HCG in each layer controls the wavefront of the 0st order diffraction. In our work, the structure and parameter for multi-layer dispersive mirrors (stacked HCGs) are designed and optimized based on numerical (FDTD and RCWA) study. For our structures, the physics behind reflection and phase shift characterization are studied. Our numerical work shows that the dispersive mirror can direct light of different wavelengths into different angles for the entire solar spectrum, maintaining very low energy loss. The dispersive mirror will be fabricated using low-cost nanoimprint lithography. Our approach does not only improve the energy harvesting efficiency, but also lower the cost by using low-cost single junction cells. Moreover, this approach has the minimum disruption to the existing infrastructure.

8824-4, Session 1

Simulation of photovoltaic performance in a thin film, hybrid heterojunction incorporating a nanoscale semiconductor spectral sensitizer

Scott Devalle, The Univ. of Arizona (United States); Jean B Kana-Kana, Materials Science and Engineering, Univ of Arizona (United States); Kelly Simmons-Potter, Barrett G. Potter Jr., The Univ. of Arizona (United States) and College of Optical Sciences, The Univ. of Arizona (United States)

Nanoscale semiconductor structures offer unique optical and electronic characteristics of significant import to enhanced solar spectral coverage and energy conversion efficiency in photovoltaics (PV). Our past work in optoelectronic CdTe-ZnO nanocomposites has identified multilength scale structural designs furnishing both tunable absorption (via quantum confinement) and effective long-range photocarrier transport. The integration of these nanostructures within established thin film heterojunction PV, however, must insure the most effective use of these materials in the context of the overall device architecture and its operation. In the present work, nanoscale CdTe was examined as a sensitizer in the context of hybrid PV heterojunctions based on ZnO and poly 3-hexylthiophene (P3HT). The role of the sensitizer and its contribution to device performance was investigated through both computational modeling of cell output characteristics and through experimental studies. The work confirms the spectral contribution of the nanophase to the heterojunction external quantum efficiency, and further demonstrates the importance of nanophase placement relative to the heterojunction plane in dictating device output. Such results provide valuable insight into carrier transport length scales and optical characteristics contributing to the design of such devices with enhanced conversion efficiency.

8824-5, Session 2

Nanostructured electrodes for organic photovoltaics *(Invited Paper)*

Nikos Kopidakis, National Renewable Energy Lab. (United States); Wounjhang Park, Univ. of Colorado at Boulder (United States)

Nanostructured back contacts offer many possibilities for improving the efficiency of Organic Photovoltaics (OPV). We discuss a simple methodology to integrate prefabricated nanostructured contacts into an OPV device, and show examples of applying it to two classes of electrodes: the first requires post-processing that is incompatible with an organic active layer and the second is a tailored nanostructure that can be used for enhanced light management in the device. The latter class of electrodes opens up new possibilities for designing photonically-active structures that can enhance the absorption of subgap photons and overcome the limitation of energy losses in the electron transfer step from the photoexcited donor to the acceptor. We will discuss the design, fabrication and characterization of photonic electrodes, their applicability to OPV and determine the spectral region where the photoresponse of the device is improved.

8824-8, Session 2

Light trapping in dye sensitized solar cells

Stephen Foster, Sajeev John, Univ. of Toronto (Canada)

The dye-sensitized solar cell (DSSC) is a promising third-generation solar cell technology, but at present lacks the power conversion efficiency to compete effectively with other solar cells on the market. In this work we demonstrate numerically that photonic crystal DSSCs can provide at least a factor of one-third enhancement in solar light absorption relative to their conventional counterparts. Our design consists of a lattice of modulated-diameter TiO_2 nanotubes filled with TiO_2 nanoparticles and interstitial regions filled with electrolyte. This provides not only light trapping and absorption enhancement, but offers improved electrical transport through the nanotube walls. The nanotube array itself forms an extended 2D photonic crystal, and the spacing and diameter of tubes in the array are chosen to promote dielectric modes that concentrate light in the interior of the tubes. Linear and sinusoidal modulation over select regions of the nanotube diameter creates a 3D photonic crystal and allow for enhanced anti-reflection and back-reflection, respectively. Further reduction of reflection losses is accomplished through the addition of triangular corrugation to the glass-air interface of the cell. Using a constant volume of dye-coated TiO_2 nanoparticles our design gives a maximum achievable photocurrent density (MAPD) of 20.8 mA/cm^2 in 2D simulations. This is a 33% improvement over the MAPD for a simple planar cell geometry, and well above the record short-circuit current density for C101-based cells. We also demonstrate that choosing a dye with a broader but weaker absorption profile compared to commonly used dyes would lead to even larger absorption enhancements.

8824-9, Session 3

Improving the light-harvesting of thin film solar cells with photochemical upconversion *(Invited Paper)*

Timothy W. Schmidt, The Univ. of Sydney (Australia)

In order to generate more cost efficient PV devices, one must look to technologies which promise to better manage the solar spectrum. One promising approach is triplet-triplet annihilation upconversion in organic molecules, whereby sub-bandgap light can be converted to usable wavelengths. I will review our latest results, applying TTA-UC to thin-film cells such as amorphous silicon, organic and dye-sensitized solar cells, and outline our strategies for achieving efficient upconversion under one sun.

8824-10, Session 3

Enhanced solar photoconversion exploiting molecular photochemical upconversion

Felix N. Castellano, Hyounsoo Uh, Bowling Green State Univ. (United States); Michael J. Therien, Jean-Hubert Olivier, Duke Univ. (United States); Andrew J. Ferguson, William Nemeth, Andrew Norman, National Renewable Energy Lab. (United States)

Over the last decade the phenomenon of triplet-triplet annihilation-assisted photon upconversion (UC) has been demonstrated for a wide variety of molecular triplet sensitizer/annihilator systems. This photophysical process exhibits great potential for the sensitization of a variety of semiconductor platforms (e.g. amorphous silicon and metal oxides) with relevance in photovoltaic (PV) and photoelectrochemical applications.

We will initially discuss efforts to photooxidize water by sensitizing nanostructured tungsten oxide (WO_3) photoanodes to sub-bandgap, non-coherent green photons at low power density, using the benchmark upconverting system palladium(II) octaethylporphyrin (PdOEP) and 9,10-diphenylanthracene (DPA) in toluene.

We will then discuss recent efforts to synthesize novel light-harvesting chromophores that (i) possess large near-infrared extinction coefficients, (ii) manifest ultrafast intersystem crossing to generate the triplet state at unit quantum yield, and (iii) possess triplet lifetimes exceeding several microseconds, which will be incorporated into molecular photon UC systems with the appropriate luminescent visible emitters. We will examine factors influencing the efficiency of the photon UC process in solution and the solid state, describe recent efforts to couple UC systems into device architectures employing transparent a-Si devices, and summarize the observed performance of the coupled UC-PV system.

8824-11, Session 3

Photonic structures for enhanced upconversion

Barbara Herter, Sebastian Wolf, Stefan Fischer, Johannes Gutmann, Benedikt Bläsi, Fraunhofer-Institut für Solare Energiesysteme (Germany); Jan Christoph Goldschmidt, Fraunhofer-Institut für Solare Energiesysteme (Germany) and Imperial College London (United Kingdom)

Upconversion of sub-band-gap photons offers a possibility to overcome the Shockley-Queisser efficiency limit for solar cells. Unfortunately, materials showing upconversion properties, still suffer from too low upconversion quantum yields (UCQY). Here, we investigate how the UCQY can be increased by embedding of the upconverter material into a photonic structure. The photonic structure has two effects: first, a local irradiance enhancement, which increases the upconversion quantum yield due to the nonlinearity of the upconversion process. Second, the local density of photonic states (LDOS) is varied due to the photonic environment. This affects the transition probabilities within the upconverter. Including these two effects shows the potential to increase the UCQY.

We present simulation results based on an FDTD-approach, where the effects of the irradiance enhancement and the LDOS are quantified. The results of these simulations are combined with a rate-equation model of the upconversion dynamics in $NaYF_4:Er^{3+}$, thus, modeling the behavior of the upconverter within the photonic structure. We show that an optimized waveguide structure can increase overall upconversion luminescence by a factor of 268 and the overall quantum yield by a factor of 9.3. For the investigated upconverter, this results in an increase of the quantum yield from 0.86?% to 8?% in the presence of the structure. The key to the successful optimization of the structure was to increase the local density of photon states at the emission wavelength of the upconverted photons.

The production of an upconverter in a suitable photonic structure is work in progress. First experimental data will be presented at the conference.

8824-13, Session 4

Nanophotonic light tapping strategies for thin solar cells *(Invited Paper)*

Mark Brongersma, Geballe Lab. for Advanced Materials (GLAM) (United States)

Nanophotonics is an exciting new field of science and technology that is directed towards making the smallest possible structures and devices that can manipulate light. In this presentation, I will show how semiconductor and metallic nanostructures can mold the flow of light well below the wavelength of light. This ability opens up the opportunity to effectively trap light in ultrathin solar and photo-electrochemical cells. I will discuss how the nanostructure sizes and shapes as well as their non-periodic arrangement on a cell can be optimized to effectively harvest solar energy from such thin cells and across the broad solar spectrum.

8824-14, Session 4

Plasmonic nanocavities: a new paradigm for ultra-thin solar cells

Andrea Cattoni, Clement Colin, Inès Massiot, Nicolas Vandamme, Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France); Christophe Sauvan, Philippe Lalanne, Institut d'Optique Graduate School (France); Jean-François Guillemoles, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); Stéphane Collin, Lab. de Photonique et de Nanostructures (France)

Efficient light confinement in nano-scale semiconductor volumes could allow for a drastic reduction in semiconductor material consumption and for further development of third-generation solar cells.

In this talk we propose a new and versatile design for broadband light trapping in ultrathin (≲100 nm) film solar cells. The design is based on Metal/Insulator/Metal plasmonic nanocavities for which we have experimentally demonstrated omindirectional total absorption of light in sub-wavelength volumes (?3/1000) [1]. By carefully designing the resonant nanoantenna array, it is possible to obtain multi-resonant light absorption inside a semiconductor placed in the gap of the nanocavity with limited absorption by the metal. This versatile approach is applied to different solar cell materials (GaAs, CuInGaSe). We demonstrate a short-circuit current of 19.8 mA/cm2 and a theoretical conversion efficiency of nearly 20 % by using a 30nm-thick GaAs absorber layer. For CIGS a short-circuit current of 30 mA/cm2 is predicted for 100nm-thick absorbing layer with a theoretical conversion efficiency up to 17 %. The fabrication of a preliminary solar cell proof of concept based on GaAs and CIGS is detailed.

The enhanced electromagnetic field intensity together with short carrier collection paths pave the way for nano-scale second generation solar cells with arbitrarily small diffusion lengths and for

the development of third generation concepts like hot carrier or intermediate band solar cells.

[1] Nano Letters, 11, 3557 (2011)

8824-15, Session 4

Nanophotonic light trapping in polycrystalline silicon thin-film solar cells using periodically nanoimprint-structured glass substrates

Jolly Xavier, Veit Preidel, Daniel Amkreutz, Tobias Sontheimer, Daniel Lockau, Philippe Wyss, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Franziska Back, Eveline Rudigier-Voigt, SCHOTT AG (Germany); Bernd Rech, Christiane Becker, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

A smart light trapping scheme is essential to tap the full potential of polycrystalline silicon (poly-Si) thin-film solar cells. Nanophotonic periodic structures are of particular interest as they allow to substantially surpassing the Lambertian limit from ray optics in selected spectral ranges. However, large-area fabrication processes have to be applied for nanostructuring in order to permit the cost-effective production of thin-film solar cell devices. In this study, we used nanoimprint-lithography enabling the nanopatterning of large-areas at low costs and high throughput. 2D periodic crystalline silicon nanoarchitectures were fabricated by evaporation, solid or liquid phase crystallization and chemical etching of thin silicon films on Schott AF glass covered by a temperature-stable nanoimprint-textured sol-gel. In this way, periodic silicon nano-/microhole arrays with varying pitch size and hole radius could be prepared on areas up to several square centimeters featuring excellent absorption properties. Poly-Si microhole arrays with 2µm pitch and an effective thickness of 1µm exhibited 44% absorption at ?=900 nm corresponding to a light path enhancement factor above 60 in crystalline silicon, i.e. beyond the Lambertian limit. The geometrical device design has been optimized experimentally and numerically with respect to a maximum optical absorption in the poly-Si volume and minimum parasitic absorption in functional layers. The distinct growth and crystallization properties of silicon on textured surfaces have been considered in order to maintain a good electronic material quality of the poly-Si absorber. These structures inspire the design of prospective applications such as high-efficient poly-Si thin-film solar cells and large-area photonic crystals.

8824-16, Session 4

Solar power conversion optimization in thin-film silicon photonic crystal solar cells

Alexei Deinega, Sergey Eyderman, Sajeev John, Univ. of Toronto (Canada)

We compare efficiency of different types of photonic crystal solar cells, namely, conical pore films and nanowires. Solving both Maxwell's equations and the semiconductor drift-diffusion in each geometry, we identify optimal junction and contact position and study the influence of bulk and recombination losses on solar cell efficiency.

For conical pore photonic crystal we use p-n junction interface which is parallel to the bottom surface. For nanowires we consider radial and axial p-n junctions. We analyze photocurrent distribution inside each structure and calculate short circuit current density and open circuit voltage for different values of diffusion lengths and surface recombination at the contact. For small diffusion lengths results do not depend on surface recombination, since most of the recombination occurs at the bulk. In this case only carriers which are close enough to the junction can contribute to the photocurrent. If diffusion length is long and surface recombination rate is high, most of the recombination occurs at the metal contacts. Reducing contact area leads to improvement of solar cell efficiency. For the case of long diffusion lengths and small surface recombination, all generated carriers contribute in photocurrent.

We find that using only one micron of silicon, sculpted in the form of inverted slanted conical pore photonic crystal film, one can achieve 80-90% absorption within the whole solar spectrum and 17.5% solar power conversion efficiency when the carrier diffusion length exceeds 50 microns. This efficiency could be improved using two different types of silicon, amorphous and microcrystalline, in a top and a bottom the cell. Opportunities for "hot carrier" collection and up-conversion of infrared light, enhanced by photonic crystal geometry, facilitate further improvements in power efficiency.

8824-17, Session 5

Multiple exciton generation in quantum dots and quantum dot solar cells *(Invited Paper)*

Matthew C. Beard, National Renewable Energy Lab. (United States)

We are investigating multiple exciton generation (MEG) in quantum dot (QD) based solar cells as a way to enhance solar energy conversion by channeling excess photon energy to produce multiple electron-hole pairs rather than heat. I will discuss recent ultrafast transient absorption studies of MEG in doped and undoped PbSe QDs, couple PbSe QD arrays, and colloidal Si QDs. If time permits I will discuss strategies for incorporating both the Pb chalcogenide and Si QDs into prototype solar cells.

8824-18, Session 5

Ultrafast exciton dynamics in CdSe nanocrystals: Auger-mechanisms and confined phonons

Bryan T. Spann, Liangliang Chen, Xiulin Ruan, Xianfan Xu, Purdue Univ. (United States)

Nanocrystal sensitized solar cells have the theoretical potential to surpass the Shockley–Queisser limit via capture of hot-electrons. Time-resolved transient absorption pump-probe spectroscopy is used to investigate exciton relaxation in CdSe nanocrystal films. The effects of morphology (quantum dots vs. quantum rods), size dependent quantum confinement, and preparation of nanocrystal films are investigated. Our experiments revealed a decrease in the confinement enhanced Stark effect in the quantum rod films as well as slower intraband relaxation times compared with quantum dots of the same diameter. The slowed relaxation in quantum rods is due to the mitigation of the Auger-relaxation pathway as a result of elongating the nanocrystal. Furthermore, our study on nanocrystal size dependence also reveals reduction in the Auger-relaxation mechanism for volumetrically larger nanocrystals. Both morphologies of the nanocrystal films showed long-lived confined acoustic phonons corresponding to the ellipsoidal breathing mode, consisting of transverse and longitudinal acoustic phonons.

8824-19, Session 5

Hot carrier solar cell absorbers: materials, mechanisms, and nanostructures

Gavin Conibeer, Santosh Shrestha, Shujuan Huang, Robert Patterson, Hongze Xia, Yu Feng, Pengfei Zhang, Neeti Gupta, Suntrana Smyth, Yuanxun Liao, Shu Lin, Pei Wang, Xi Dai, Simon Chung, The Univ. of New South Wales (Australia)

An ideal Hot Carrier cell would absorb a wide range of photon energies and extract a large fraction of the energy to give very high efficiencies, up to 65% at 1sun (85% at max concentration), by extracting 'hot' carriers before they thermalise to the band edges. The key property for a hot carrier absorber is to slow the rate of carrier cooling from the picosecond timescale to at least 100s of ps. Hot carriers cool primarily by emission of LO phonons.

Multiple QW structures have demonstrated reduced carrier cooling by enhancing the phonon bottleneck, prior to optical phonon decay. Large phononic band gap materials would seem to have strong potential to block Klemens' decay of optical phonons and thus also increase phonon bottleneck. A hot carrier absorber combining both structures should give even greater reduction in carrier cooling rates as the mechanisms should not interfere directly with each other and hence their effects should be additive. A Hot Carrier cell design combining MQW with phononic band gap materials could use InN/InGaN wells and barriers. This would combine the MQW effect with phononic band gap. Later designs would incorporate the more abundant transition nitrides or group IV compounds in MQW structures with phononic band gap materials, to lead to even greater retardation of carrier cooling.

Fabrication of materials that can slow carrier cooling through enhancing phonon bottleneck is challenging. Investigation of the mechanisms in large mass difference materials and superlattice structures will be presented and options for combined devices discussed.

8824-20, Session 5

PbS quantum dot thin film solar cells using a cds window layer

Khagendra P. Bhandari, Hasitha Mahabaduge, Paul J. Roland, Neale O. Haugen, Corey R. Grice, The Univ. of Toledo (United States); Sohee Jeong, Korea Institute of Machinery & Materials (Korea, Republic of); Tieneke Dykstra, The Univ. of Toledo (United States); Jianbo Gao, National Renewable Energy Lab. (United States); Randy J. Ellingson, The Univ. of Toledo (United States)

Here we report on heterojunction thin film solar cells in which we deposit a thin PbS quantum dot (QD) layer atop a sputtered CdS n-type window layer. Fabrication of a PbS QD-based thin film consists of depositing a ~200 nm thick film of PbS QDs using a layer-by-layer (LbL) dip coating method in which the as-prepared oleic acid ligands are replaced with a short-chain molecule, 1,2-ethanedithiol. Such a thin film affords reasonable charge carrier mobilities while retaining quantum confinement. In our heterojunction devices, we sputter (via RF magnetron sputtering) an n-type window layer, onto patterned ITO and subsequently fabricate a quantum dot thin film and complete the device with a top metal contact. These solar cells generate open circuit voltage in excess of previous reports based on PbS QDs heterojunctioned with other materials. We report on investigations of the influence on device performance of CdS film thickness and PbS QD diameter, and find optimal parameters to be 70 nm CdS layer thickness and ~2.7 nm PbS QD diameter (Eg ~1.60 eV). Under standard AM1.5G illumination, we observe short circuit current as high as 13 mA.cm-2, yielding a maximum efficiency of 3.3%. We also apply photoelectron spectroscopy contactlessly, and quantitatively to measure the valence and conduction band offsets at abrupt heterojunction interfaces between CdS/PbS QDs system.

8824-21, Session 5

Super-absorption in sparse arrays of III-V nanowire optical waveguides for photoelectrochemical and photovoltaic applications

Katherine T. Fountaine, Shu Hu, Nathan S. Lewis, Harry A. Atwater Jr., California Institute of Technology (United States)

GaAs and other III-V compound nanowire (NW) arrays represent an approach to enable high-quality, lattice-mismatched growth via radial strain relaxation, and also to reduce material usage and cost of photovoltaic and photoelectrochemical devices. Even at very low areal fill fractions, GaAs NW arrays exhibit strong absorption due to coupling into radial optical waveguide modes. We report here the very strong light absorption (60-100% of incident light) and current collection properties of sparse (<5% fill fraction) III-V NW arrays grown on both GaAs and Si substrates, supported by experiments, simulations and analytical theory. These absorption characteristics indicate a 15-25x enhancement in the effective cross section of the NWs that is strongly dependent on wavelength and incidence angle.

Optical absorption and electrochemical photocurrent collection was performed for MOCVD-growth NW arrays (wire length~3um, wire diameter~150nm, pitch~600nm) as a function of wavelength (350-900nm) and illumination angle (0-60°) was measured experimentally and modeled via three-dimensional, full-field electromagnetic simulations. Experiments, electromagnetic simulations and analytical modal analysis showed excellent qualitative and quantitative agreement across the spectrum and range of incident angles. The identification of specific TE and TM optical waveguide modes that are responsible for absorption peaks was carried out via a comparison of analytical solutions using fundamental optical waveguide theory and the spatially-resolved electric field profiles of the wire cross sections obtained from electromagnetic simulations.

Ultimately, the elucidation of the mechanism responsible for the high absorption of sparse III-V NW arrays facilitates optimization of light absorption and, thus, improves III-V NW array optoelectronic performance.

8824-22, Session 5

Light trapping enhancement in ordered and disordered silicon nanowire based solar

Martin Foldyna, Ecole Polytechnique (France)

In order to reduce the fabrication cost of solar cells, the recent focus of many research groups is towards thin film solutions. To achieve high energy conversion efficiency of the thin film solar cells, the light management must be significantly boosted by an efficient light trapping scheme. One efficient way to maximize conversion efficiency of thin film solar cells is to use radial junction silicon nanowire based solar cells. The main advantages of radial junction solar cells include the high built-in field (due to the radial geometry) and efficient light trapping (due to the good absorption and scattering properties of nanowires).

In this work we compare the light trapping enhancement obtained on random nanowire based solar cells grown using plasma-assisted vapour-liquid-solid (VLS) method with the enhancement in periodic vertical nanowire arrays. Periodic arrays are modelled using rigorous coupled wave method, while the light trapping inside disordered nanowire solar cells is estimated based on the experimental data. Our results show the impact of the nanowire density and length on the light trapping enhancement in ordered and disordered nanowire solar cells. The comparison provides better understanding, needed for the optimization of silicon nanowire based solar cells fabricated using VLS method.

8824-23, Session 6

Solar light trapping in slanted conical-pore photonic crystals

Sergey Eyderman, Sajeev John, Univ. of Toronto (Canada)

We demonstrate by FDTD simulation that a solar cell with only one micron, equivalent bulk thickness, of crystalline silicon, sculpted into the form of a slanted conical-pore photonic crystal and placed on a silver back-reflector, it is possible to attain a maximum achievable photocurrent density (MAPD) of 35.5mA/cm2 from impinging sunlight. This corresponds to absorbing roughly 85% of all available sunlight in the wavelength range 300-1100nm and exceeds the limits suggested by previous “statistical ray trapping” arguments. The optimum carrier generation occurs for a photonic crystal square lattice constant of 850nm and slightly overlapping inverted cones with upper (base) radius of 500nm.

It is also shown that using only two hundred nanometers, equivalent bulk thickness, of gallium arsenide, forming a same slanted conical-pore photonic crystal packaged with SiO2 and deposited on a silver back-reflector, one can obtain a MAPD of 26.3mA/cm2, which is 90% of absorption of all available sunlight in the wavelength range 400-855nm and occurs for a photonic crystal square lattice constant of 550nm and inverted cones with radius of 300nm.

We show that our structures possess strong anti-reflective and light trapping properties and absorb light within slow group velocity modes, that propagate nearly parallel to the solar cell interface and exhibit localized high intensity vortex-like flow in the Poynting vector-field. Presented angular distribution of the MAPD indicates that in both cases there is no substantial degradation in the MAPD at least up to ? = 50o for various directions of incidence and polarizations.

8824-24, Session 6

Multilayer structures with highly directional absorptivity for solar thermophotovoltaics

Christopher H. Granier, Francis O. Afzal, Georgios Veronis, Jonathan P. Dowling, Louisiana State Univ. (United States)

Solar energy is an ideal technology for power generation because it is clean, quiet, and renewable. Photovoltaic solar cells can provide virtually unlimited amounts of energy by effectively converting sunlight into clean electrical power. However, significant improvement in the efficiency of photovoltaic solar cells is required to make them competitive with grid power. In this paper, we explore an approach to enhance the efficiency of solar cells using photonic nanostructures for solar thermophotovoltaics. Thermophotovoltaic solar cells, where solar radiation is absorbed by an intermediate absorber, which then emits thermal radiation towards a solar cell, are capable of achieving extremely high efficiency using single-junction solar cells. The theoretical efficiency of 85% far exceeds the Shockley-Queisser limit of 41% when a single-junction cell is directly exposed to sunlight. In order to approach such efficiency, however, there are very important constraints on the properties of the intermediate absorber and emitter. Here our focus is on designing photonic nanostructures that can provide broadband absorption in a narrow angular range. This is a crucial requirement for solar thermophotovoltaic systems which do not employ sunlight concentration. We consider a structure consisting of an aperiodic multilayer stack of alternating layers of silicon and silica on top of a thick tungsten layer. The layer thicknesses are optimized using a genetic global optimization algorithm in combination with a transfer matrix formalism to maximize the angular selectivity in the absorptivity for both TE and TM polarizations. Using such an approach, we design structures with highly directional absorptivity for both polarizations.

8824-25, Session 6

Minimizing light reflection from textured surfaces

Alexei Deinega, Univ. of Toronto (Canada); Ilya Valuev, Joint Institute for High Temperatures (Russian Federation); Yurii E. Lozovik, Institute of Spectroscopy (Russian Federation); Boris Potapkin, Russian Research Ctr. Kurchatov Institute (Russian Federation)

We study antireflective properties of pyramidally textured surfaces for all texture size-to-wavelength ratios. In the case when the wavelength is much smaller than the feature size of the texture, we use the geometric optics approach and ray tracing. In the long-wavelength limit we use the effective medium theory (EMT). As a main tool we use the finite-difference time-domain (FDTD) method which is valid for all texture size-to-wavelength ratios, including effective medium and geometric optics limits. In both limiting cases we compare the theoretical reflection coefficients with the results obtained using direct FDTD simulation.

It was found that the key factor, influencing the optimal size of the pyramidally textured surface, is the character of the substrate tiling by the pyramid bases. We have shown analytically, that in the case of a complete tiling (for example, when the pyramid bases are regular hexagons fully packed in triangular lattice) the EMT approximation predicts polynomial decay of the reflectance when pyramids height increases. In the geometric optics limit this decay is exponential. This leads to the fact, that the minimal reflectance can be achieved at the macroscopic sizes of the pyramids. In the case of an incomplete tiling (for example, for cones as texture elements) the reflectance approaches a constant value in the EMT limit, and in the geometrical optics limit tends to the reflectance of the bare substrate. As a result, for an incomplete tiling, which is usual for technological reasons, the minimal reflectance is predicted at the pyramid sizes of the order of the wavelength. This prediction is confirmed by the direct FDTD calculations performed in the whole sizes range. To illustrate our theoretical and computational results we compare them with the experimental data for silicon solar cells with textured surface.

8824-12, Session PMon

Down-conversion effect on GaAs single junction solar cell using CdSe quantum dots

Joon-Suh Park, Jihoon Kyhm, Hyungduk Ko, Jin Dong Song, Eunkyeom Kim, Il Ki Han, Korea Institute of Science and Technology (Korea, Republic of)

With the growing need of more effective energy harvesting, solar energy has been sought as one of the prominent candidates among the eco-friendly methods. Although many types of solar cells have been developed, the electronic conversion efficiency is limited by the material's physical properties: solar cells can only harvest solar energy from limited range in solar energy spectrum. To overcome this physical limit, we approach by using the down-conversion effect with conventional CdSe quantum dots (QDs), transforming high energy photons to low energy photons to the range the designated solar cell has higher probability of electron-hole generation. In our study, we have fabricated GaAs single junction solar cells grown by molecular-beam epitaxy (MBE) and applied CdSe quantum dots for down-conversion. We examine the effects of such application on the solar cell efficiency, fill-factor, JSC, VOC, etc. We observed noticeable increase in photocurrent and energy conversion efficiency. Also, using time-resolved photoluminescence technique, we observe the changes in decay time of CdSe QD and carrier lifetime in GaAs solar cell which occurs possibly by down-conversion effect. This work was supported by KIST Flagship Project, project number 2E23892.

8824-36, Session PMon

Biomimetic antireflective AlInP nanostructures fabricated by lithography-free method for solar cell applications

Chan Il Yeo, Joon Beom Kim, Kwang Wook Park, Yong Tak Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

III-V compound semiconductor solar cells have been considered as a promising candidate for high solar power generation due to their superior conversion efficiency. However, the high Fresnel reflection originating from the large refractive index mismatch between air and semiconductor material, limits the conversion efficiency. To improve the cell efficiency by suppressing the unwanted Fresnel reflection, a great deal of efforts has been explored using various surface structures. Recently, biomimetic antireflective nanostructures inspired from the nature called as "moth-eye" have attracted great attention due to their broadband and omnidirectional antireflection properties. To produce such antireflective structures, dry etching using etch mask patterns having nano-scale dimensions, which are usually formed by lithography method, has been widely utilized. However, the lithography based nanopatterning techniques are complex, expensive, and therefore not suitable for mass production.

In this work, we fabricated antireflective nanostructures on AlInP, which is a common material for window layer of compound semiconductor solar cells, by inductively coupled plasma etching using Ag etch mask, which was easily formed by spin-coating of Ag ink and subsequent sintering process on a hotplate (under 250°C) without any sophisticated equipments. This lithography-free method is a simple, cost-effective, and high throughput method. The fabricated AlInP nanostructures demonstrated drastically reduced solar-weighted reflectance (SWR) of 2.95% compared to that of bulk AlInP (28.75%) in the wavelength range of 300-870 nm. The incident angle dependent SWR of the fabricated AlInP nanostructure remained below 5% up to an incident angle of 50°. Therefore, the fabricated AlInP nanostructures using lithography-free method hold great potential for use in solar cells.

8824-37, Session PMon

A silicon template with a high aspect ratio nanoscale structure realized by a two-step etching method for a stamping technique

Dae-Seon Kim, Dong-Hyun Kim, Sungbae Lee, Jae-Hyung Jang, Gwangju Institute of Science and Technology (Korea, Republic of)

Subwavelength structures (SWSs) have been considered as an alternative to single-layer or multilayer antireflection coatings (ARC) to reduce the surface reflection of solar cells due to their broadband antireflective property. An array of nanoscale structures can lead to gradual changes of the effective refractive index at the surface, which contributes to decreasing the surface reflection under a wide wavelength range. The shape and aspect ratio of a nanoscale structure are crucial parameters to realize an optimized transition of the effective refractive index from the bottom of structure to the air. To realize SWS as an ARC on a solar cell, many direct lithographic approaches have been utilized on the top surface of the solar cell. These conventional methods have drawbacks associated with their complicated processes. Recently, stamping methods have been proposed due to their potential advantage of simple manufacturing. By pressing the template with a negative pattern of a nanoscale structure onto a polymeric material, the SWS is easily transferred. In this study, electron-beam lithography was utilized for the initial formation of a 350-nm-period hexagonal pattern with a 40-nm-diameter hole on a 100-nm-thick SiO_2-coated silicon substrate. Next, a two-step etching process combined with the wet etching of SiO_2 and the dry etching of silicon was carried out to create silicon templates with nanoscale structures of various appearances with aspect ratios higher than 2.5. The hexagonal pattern with an enlarged hole was then transferred to the final silicon template. By adjusting the parameters of the two-step etching condition, the aspect ratio and the shape of the structure were controlled, resulting in various silicon templates. The polymeric SWS was fabricated by silicon template and stamping technique. The fabrication details and the optical results of the polymeric SWS will also be discussed.

8824-38, Session PMon

Spectrum upconversion and downconversion in (Tm^{3+}, Yb^{3+}) and (Tb^{3+}, Yb^{3+}) co-doped fluorosilicate glass

Zhengda Pan, Richard Akrobetu, Steven H. Morgan, Fisk Univ. (United States)

We investigated the spectrum upconversion and downconversion in Tb^{3+}, Tm^{3+}, and Yb^{3+} co-doped fluorosilicate glass, aiming to reduce solar energy loss due to the sub-bandgap transmission of long wavelength photons and/or the thermalization of excess excited charge carriers by high energy photons. The rare-earth doped glasses were fabricated in a SiO_2-Al_2O_3-Li_2O-LaF_3 matrix using a melt-quench technique. Upon excitation at 980 nm, strong visible upconversion luminescence was observed between 450 nm and 840 nm, which can enhance the performance of CdTe solar cells, because the crystalline CdTe has an energy gap of 1.45 eV, corresponding to a cut-off wavelength of 855 nm. Upon blue light excitation, downconversion luminescence was observed between 920 and 1040 nm, matched well with the bandgap of the crystalline Si. Our spectrum conversion results indicate that the upconversion and downconversion efficiencies depend on the rare-earth doping concentrations as well as on the concentration of the incident light (the light irradiance). We attribute the spectrum conversions observed to the cooperative energy transfer and/or the excited state absorption mechanisms of the rare-earth ions in the glass. The luminescent glass developed can act as a spectrum convertor located on the front surface of a solar cell, therefore enhancing the light-to-electric energy conversion of a PV solar cell. The rare-earth doped glass shows promise to have high spectrum conversion efficiency and therefore may find its applications in PV solar cells for a higher light-to-electric energy conversion efficiency.

8824-39, Session PMon

High efficiency solar cell with ZnO/CdS/CdSe nanowire array

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Nowadays, a series of nano-photovoltaic devices based on ZnO nanowire array have been widely studied due to the excellent optical properties of ZnO. ZnO nanowire array can be synthesized in an easy, low cost, environmental-friendly method. The performance of solar cell with ZnO electrodes is largely depending on the morphology and crystal qualities of ZnO nanowires.

Herein, we presented the synthesis and photovoltaic application of ZnO nanowire array with three different growth methods. Based on the basic source of the hydrothermal growing solution, ZnO nanowire array was prepared by the a) ammonia solution (N), the b) hexamethylene tetramine (H) and the c) alternation of ammonia and hexamethylene tetramine (NH). Firstly, ZnO nanowire array was grown on ITO glass using the above three methods. The ZnO nanowire array with a length of about 16μm has been obtained Secondly, the ZnO/CdS core/shell heterojunction nanowire array was fabricated by depositing CdS nanocrystals on the surface of ZnO nanowires to offer an interlay to reduce the charge recombination on the ZnO nanowires. Then, the CdSe QDs were deposited on the surface of the ZnO/CdS nanowires to absorb photons and transfer charge carriers to ZnO nanowires. Finally, solar cells were constructed and optimized with polysufide electrolyte and CoS counter eletrode. The results indicate that the photovoltaic behavior depends on crystal quality and morphology of ZnO nanowire array. Hence, we observe an increasing efficiency as follows: N< NH< H. The best power conversion efficiency of 3.88% was obtained.

8824-40, Session PMon

Patterned crystalline Si solar cells for better light trapping

Dong-Wook Kim, Yunae Cho, Eunsongyi Lee, Minji Gwon D.V.M., Ewha Womans Univ. (Korea, Republic of); Joondong Kim, Kunsan National Univ. (Korea, Republic of)

Recently, there have been intensive researches on development of ultrathin Si absorber-based solar cells to realize high-efficiency and low-cost photovoltaic devices. In addition to the conventional anti-reflection coating and surface texturing techniques, patterned absorbers have emerged as an alternative light trapping structures. Through numerous attempts to design optimal patterned structures, calculation results have shown that the patterned structures exhibit omni-directional and enhanced optical absorption, compared with the planar counterparts. The efficiencies of the fabricated patterned cells, however, have not surpassed those of the conventional cells primarily due to recombination loss at the enlarged surface area.

In this study, we have fabricated and investigated photovoltaic performance of micro-patterned crystalline Si solar cells. The depth of the hole is only 2 ?m, and hence the electrical characteristics of the p-n diode does not show any signature of deterioration compared with the planar device. To investigate the optical properties of the patterned cells, we perform finite-difference time-domain (FDTD) simulations (Lumerical FDTD Solutions). The calculated field distribution clearly reveals the patterns concentrate the optical field near the surface with the help of the geometric antireflection effect due to the low optical density and grating-coupled excitation of optical modes. Comparative investigation of experimental and simulation results suggest importance of the carrier collection efficiency in the patterned cells.

8824-41, Session PMon

Nanostructured upconvertors for thin film solar cells

Rowan W. MacQueen, Timothy W. Schmidt, The Univ. of Sydney (Australia)

Photochemical upconversion involving triplet-triplet annihilation in organic molecules is invoked in order to address a higher limiting efficiency for solar cells, beyond the Shockley-Quiesser limit. In order that triplet-triplet processes dominate over the first order decay, a high concentration of sensitizer material is required. We have developed solid-state sensitizer materials for upconversion by binding metallated porphyrin molecules to silica nanoparticles. This has the advantage of achieving a high concentration while preventing unwanted triplet-triplet interactions between sensitizer molecules. Efficient quenching of phosphorescence is observed, indicating transfer of excitations to the emitter material. Initial developments towards an all solid state upconvertor will be reported.

8824-26, Session 7

Overview of optical rectennas for solar energy harvesting *(Invited Paper)*

Garret Moddel, Univ. of Colorado at Boulder (United States); Zixu Zhu, Univ of Colorado at Boulder (United States); Saumil Joshi, Bradley Pelz, Univ. of Colorado at Boulder (United States)

Although the concept of using optical rectenna for harvesting solar energy was introduced four decades ago, only recently has it invited a surge of interest, with dozens of laboratories around the world working of various aspects of the technology. In an optical rectenna a submicron antenna is connected to an ultra-high-speed diode, so that the incoming radiation is received and rectified to produce DC output power. The result is a technology that can be inexpensive, using only low-cost materials, and efficient. Conventional classical rectification theory does not apply at optical frequency, necessitating the application of quantum photon-assisted tunneling (PAT) theory to describe the device operation. At first glance it would appear that the ultimate conversion efficiency is limited only by the Landsberg limit to 93%, but a more sober PAT analysis that includes limitations due to the coherence of solar radiation leads to a result that coincides with the Trivich-Flinn limit of 44%. Innovative antenna designs are required to achieve high efficiency at frequencies where resistive losses in metal are substantial. The most commonly incorporated diode makes use of electron tunneling through ultra-thin metal/insulator/metal (MIM) diodes. The most severe constraint is that the impedance of the antenna and diodes must match for efficient power transfer. The consequence is an RC time constant that cannot be achieved with parallel-plate MIM diodes, leading to the need for real innovations in diode structures. Technologies under consideration include sharp-tip and traveling-wave MIM diodes, and graphene geometric diodes. We survey the technologies under consideration.

8824-27, Session 7

A new method for optical rectification using nanoscale rectennas

Nicholas M. Miskovsky, Paul H. Cutler, Peter B. Lerner, Scitech Associates, LLC (United States); James M. Chen, The Pennsylvania State Univ. (United States); Alexandre Mayer, Univ. of Namur (Belgium)

In this talk we present a new and viable method for optical rectification. This approach has been demonstrated both theoretically and experimentally and can be used for the development of a practical rectification device for the electromagnetic spectrum including the visible portion. This technique for optical frequency rectification is based, not on

conventional material or temperature asymmetry as used in MIM (Metal/Insulator/Metal) or Schottky diodes, but on a purely geometric property of the antenna tip or other sharp edges that may be incorporated on antennas. This "tip" or edge in conjunction with a collector anode constitutes a tunnel junction connected to the external circuit. The rectenna (consisting of the antenna and the tunnel junction) acts as both the absorber of the incident radiation and the rectifier. Using current nanofabrication techniques and the selective Atomic Layer Deposition (ALD) process, arrays of rectennas with junction-gaps of 1 nm can be fabricated, allowing rectification of frequencies up to the blue portion of the spectrum. In order to assess the viability of our approach, we review the state of development of nanoantenna structures, which can respond to and capture radiation through the visible region. In addition, we describe the state of development, both experimentally and theoretically, of tunnel junctions capable of operating in the visible region. Specifically, we review the process of rectification, and experimental data and theoretical work on optical rectification. Finally, we present operational designs for an optical rectenna and its fabrication.

8824-28, Session 7

Bounds for the rectification efficiency of solar radiation

Heylal Mashaal, Jeffrey Gordon, Ben-Gurion Univ. of the Negev (Israel)

We derive fundamental efficiency limits for the rectification (conversion of AC to DC) of incoherent broadband radiation, motivated by the paradigm of solar power conversion by rectifying antennas. For an individual full-wave rectifier, the bound is comparable to the (unrelated) efficiency bound for solar conversion via photovoltaics under high flux concentration with multi-junction cells. We also derive the efficiency boosts that can be obtained with cascaded rectifiers.

8824-29, Session 7

Coherence and thermal noise effects in arrays of nanoscale antennas

Peter B. Lerner, Nicholas M. Miskovsky, Paul H. Cutler, Scitech Solar (United States); Alexandre Mayer, Univ. of Namur (Belgium)

The fact that blackbody radiation from a radiator, which has a size comparable to the thermal wavelength ?_T=2π?c/(k_B T) has certain coherence properties has been established a long time ago. Now, with the possibility of making microscopic dense arrays of antennas smaller in scale than the optical wavelength, one might consider applications for the coherence properties of such antennas. Moreover, with possible variations in the the geometry, we analyze the nanoantenna array as a collection of blackbody radiators with some effective temperature and associated noise spectrum. This paper discusses the use of these arrays as sensors in the infrared and visible parts of spectrum and its dependence on geometry and effective temperature.

8824-31, Session 7

Step tunneling enhanced asymmetry in metal-insulator-insulator-metal (MIIM) diodes for rectenna applications

Nasir Alimardani, John F. Conley Jr., Oregon State Univ. (United States)

Thin film metal-insulator-metal (MIM) tunnel devices have experienced a renewal in interest for high speed applications such as optical rectennas for IR energy harvesting, infrared (IR) detectors, hot electron transistors, and macroelectronics. For many of these applications, desired figures of merit include high asymmetry, strong nonlinearity, and fast responsivity of current vs. voltage (I-V) behavior. The standard approach to achieving these in tunnel devices is M1IM2 diodes - the use of metal electrodes with different work functions (?M1 ≠ ?M2) to produce a built in voltage. However, the degree of asymmetry achievable using this approach is limited by the ??M. An alternative approach is to use nanolaminate pairs of insulators to introduce an asymmetric tunnel barrier so that electrons experience a different shape barrier depending on the direction of tunneling / applied bias polarity. Asymmetry may be enhanced either through resonant tunneling or step tunneling. For an appropriate choice of insulators, step tunneling can be observed. In this work, we report step tunneling enhanced properties. MIIM diodes were fabricated on smooth bottom electrodes (ZrCuAlNi or TaN) using nanolaminate pairs of insulators (HfO2, Al2O3, ZrO2) deposited via atomic layer deposition (ALD), and Al top electrodes. Conduction mechanisms were investigated as a function of temperature and field. We combine ALD nanolaminate bilayer tunnel barriers with asymmetric electrodes to produce enhanced I-V asymmetry and non-linearity in M1IIM2 devices. This result represents an advancement in the understanding needed to manufacture high quality thin film tunnel devices for microelectronics applications.

8824-32, Session 8

Prospects of graphene electrodes in photovoltaics *(Invited Paper)*

Kaustav Banerjee, Univ. of California, Santa Barbara (United States)

Transparent conductors (TC) are an essential part of modern electronics and photonics commonly found in touch panels, displays, light emitting devices, light sensors and solar cells. The market for transparent electrode is growing rapidly, and is projected to surpass $11 billion in 2016. The technical requirements for TCs in solar cell applications are sheet resistivity less than 10 ?/square and optical transparency of larger than 90%.

Few layer graphene (FLG) is a strong candidate to replace the widely used Indium Tin Oxide due to its high optical transmittance, high electrical conductivity, high-flexibility as well as impermeability to moisture (leading to improved reliability). In particular, graphene synthesis by chemical vapor deposition (CVD) (which is the only way of producing large area graphene transferrable to any substrate) allows the use of graphene as electrode material in solar cells.

In this paper, the prospects of few layer graphene for transparent conductor application in solar cells will be presented. It will discuss trade-offs between the film thickness and the optical and electrical conductivities that are needed for optimization of these structures. In the process, we will discuss methods to synthesize FLG (less than 4 layer) with high quality in a controllable manner. Furthermore, doping of FLG via various methods will be discussed that presents new opportunities in improving the performance of FLG as a TC. The integration of FLG based TCs with semiconductors is another important challenge in the development of FLG based TCs. Hence, we will discuss optimization of the interface between FLG and semiconductors including the interactions of FLG with semiconductors, which is necessary for achieving high performance photovoltaic devices.

8824-33, Session 8

Solar vapor generation enabled by nanoparticles

Oara Neumann, Alexander S. Urban, Jared Day, Surbhi Lal, Peter Nordlander, Naomi J. Halas, Rice Univ. (United States)

Solar illumination of broadly absorbing metallic nanoparticles dispersed in a liquid produces vapor without the requirement of heating the fluid volume. Energy captured by light-harvesting nanoparticles is primarily directed to the vaporization of water into steam eliminating the energy-intensive requirement of electrically heating the fluid volume.

Nanoparticle produced steam can be applied to a wide range of solar energy applications including distillation, desalination, sterilization, and sanitation. We demonstrate a high mole fraction of ethanol distillate compared with thermal-flash distillation due to the inherently non-equilibrium vaporization process using solar-powered nanoparticle heating. Additionally, the vaporization process also leads to the production of saturated steam which is ideal for sterilizing medical tools or waste. The rapid transfer of heat of saturated steam is extremely effective in denaturing proteins and may be used to destroy most known types of infectious agents, (i.e. bacteria, viruses). Complete sterilization using nanoparticle produced steam at 135°C in a 14.2 liter autoclave was verified using a standard Geobacillus stearothermophilus-based biological indicator.

8824-34, Session 8

Optoelectronic design and growth of III-V/Si tandem microwire photovoltaics

Christopher T. Chen, Daniel B. Turner-Evans, Hal Emmer, California Institute of Technology (United States); Shaul Aloni, Lawrence Berkeley National Lab. (United States); Harry A. Atwater Jr., California Institute of Technology (United States)

Tandem III-V/Si microwire arrays combine the advantages of low cost, flexible, wafer-free vapor-liquid-solid grown microwire array technology with significantly higher energy conversion efficiency potential due to better utilization of the incident solar spectrum. By tailoring the contact area between the Si microwire substrate and the III-V epilayer through selective epitaxy, a wide range of device geometries can be achieved experimentally. In this work, we consider three designs which constrain the contact area between the III-V top cell and the Si microwire bottom cell: (1) a “tipped” structure, where only the last 2 ?m of a Si microwire is coated, (2) a “spike-tipped” structure, where the Si microwire is grown to a sharp point and coated on the final 2 ?m, and (3) a “tube” structure, where the Si is etched back into a thermal oxide grown around the wire. All three designs are demonstrated using low pressure metalorganic chemical vapor deposition of Ga1-xInxP on specially prepared Si microwire substrates. Cathodoluminescence and photoluminescence are used to evaluate the material quality at nano- and macro- length scales, respectively. Scanning electron micrographs of each structure are used to create 2D coupled full field optical and device simulations using the Synopsys Sentaurus TCAD package. Current matched device tandem device designs for all three geometries are achieved, and realistic materials parameters are used to predict device performance.

8824-35, Session 8

A new method of photo-induced electrodeposition of PEDOT with silicon nanowires as electrode to form hybrid solar cells

Mingxuan Zhu, Judikaël Le Rouzo, Institut Matériaux Microélectronique Nanosciences de Provence (France); Marielle Eyraud, Lab. Chimie Provence (France); François R. Flory, Institut Matériaux Microélectronique Nanosciences de Provence (France)

Recently a new hybrid core-shell solar cell can reach more than 5% conversion efficiency. And these cells are realized by spin coating PEDOT:PSS on silicon nanowires array. The main drawback of spin coating method is bad contact quality of PEDOT:PSS on silicon wire surface, because the large size of PEDOT:PSS particles limits its penetration into the gap between wires.

Compared with spin coating, the electrochemical method can control the PEDOT film volume by determining the quantity of reaction charges during deposition. Another advantage over spin coating is tunable doping level of PEDOT that is related to quantity of anions involved into the polymer. The conformality of PEDOT coating single silicon wire can be influenced by many parameters including concentration of monomer, solvent, polarization bias, illumination intensity and so on.

Using cyclic voltammetry method, the anodic potential range for PEDOT formation is determined on silicon NW. It has been shown, by using SEM observations coupled with EDS analysis, that the PEDOT film can be successfully deposited on silicon nanowires array with electrochemical method under illumination. The illumination is necessary for PEDOT polymerization, while only little volume of polymer is fabricated in the dark.

The electro-optical measurements of such a structure will be presented and the interest of this heterojunction for nanowires silicon solar cells will thus be determined.

8825-26, Session PMon

Application of acetate, lactate, and fumarate as electron donors in microbial fuel cell

Oresta M. Vasyliv, Oleksandr I. Bilyy, Yaroslav P. Ferensovych, Svitlana O. Hnatush, Ivan Franko National Univ. of L'viv (Ukraine)

Microbial fuel cells (MFCs) are devices that use bacteria as the catalysts to oxidize organic and inorganic matter and generate current. Up to now, several classes of extracellular electron transfer mechanisms have been elucidated for various microorganisms. Shewanellaceae and Geobacteraceae families include the most of model exoelectrogenic microorganisms. Desulfuromonas acetoxidans bacteria inhabit aquatic sedimental environments and are philogenetically close to representatives of Geobacteraceae family. They are proposed to be used as a biocatalyst for MFCs because of high electron recovery (>80%) to the electric current in the process of organic matter oxidation. Two chamber MFC with volume 0.3 l was constructed with application of D. acetoxidans as anode biocatalyst. Acetate, lactate and fumarate were separately applied as organic electron donors for bacterial growth in microbial fuel cell. Bacterial cultivation in MFC was held during twenty days. Usage of lactate caused electric power production with the highest value up to 71.5 ?W on the third day of D. acetoxidans growth. Addition of fumarate and acetate into bacterial growth medium caused maximal power production up to 74.5 and 75.2 ?W respectively on the second day of their cultivation. Increasing of incubation time up to twentieth day caused decreasing of generated electric power till 20 ?W, 42 ?W and 43 ?W under usage of lactate, fumarate, and acetate respectively in anode chamber. As a conclusion, effectiveness, longevity and durability of constructed MFC on the basis of D. acetoxidans bacteria increased under addition of acetate and fumarate in anode chamber in comparison with lactate.

8825-27, Session PMon

System high voltage stress degradation test in various photovoltaic modules and encapsulant sheets

Han-Chang Liu, Wen-Kuei Lee, Mei-Hsiu Lin, Chung-Teng Huang, Fu-Ming Lin, Jen-Loong Huang, Industrial Technology Research Institute (Taiwan)

In this paper we review various PV module type, example MG-Si, poly-Si, CIGS module and encapsulant sheets performance suffer high voltage stress effect. To evaluate module durability in the presence of continuous high voltage we used three accelerated tests to qualify the HVS effect. The first one is under room temperature, 100% relative humidity, second method is room temperature and Al foil covered the front sheet and the last method is climatic chamber test at 85?and 85% relative humidity with -1000V bias applied to active layer, respectively. The I-V characteristics and Electroluminescence (EL) images have been measured after several time steps to quantify the degradation process of each module. Besides the recovery characterization was also investigation.

8825-28, Session PMon

Accelerated environmental aging and in-situ functional testing of commercial photovoltaic modules

Barrett G. Potter Jr., Kelly Simmons-Potter, The Univ. of Arizona (United States) and College of Optical Sciences, The Univ. of Arizona (United States)

Flat plate photovoltaic modules embody a complex assembly of varied material systems. Despite exposure to often adverse environmental conditions, the performance of these devices must be reliably maintained. With a functional lifetime strongly dependent on field conditions as well as on materials selection and design, an understanding of the relationship between these interrelated issues and the potential for performance degradation over the long-term is a continual goal, especially as new photovoltaic junction systems and module designs are developed.

The presentation will describe the investigation of environmental aging effects in commercially available, poly- and mono-crystalline Si PV modules. We have developed a full-scale environmental chamber equipped with single-sun irradiance capability providing illumination uniformity of 98% over a 2 x 1.6 m area. Time-dependent, photovoltaic performance (I-V characteristics) is evaluated over a compressed night-day cycle providing 6 hours of single-sun irradiance, representative of solar irradiance averages in the southwestern United States, followed by six hour dark (night) period. A total test time of 3.5 months of these cycles corresponds to year of exposure on a fielded module. Temperature and humidity maxima and minima used in the study range from 18°C, 62%Rh to 3°C, 32%Rh to simulate the coldest winter months, up to 37°C, 56%Rh to 23°C, 28%Rh to simulate the hottest summer months. Early results confirm the impact of environmental conditions on the module long-term performance. Correlation of these in-situ functional tests, a unique opportunity offered by this facility, with physical degradation of the modules is examined.

8825-29, Session PMon

Luminescence radiation spectroscopy of silicon solar cells

Radek Stojan, Jiri Vanek, Martin Mal?, Roman Gvritishvili, Lucie ?imonová, Ondrej Frantík, Brno Univ. of Technology (Czech Republic)

At present there are known many of diagnostic methods of detection large crystal lattice defects of silicon solar cells. This paper deals about results of new potential in to use one of characteristics luminescence radiation for detection defects of solar cells. So polarization spectroscopy of defect in solar cells may be used to fitting characterization of silicon solar cells. And this can lead to understand the electrical properties of defects in silicon solar cells and study of really formation defects. We extend the existing electroluminescence technology about polarization spectroscopy to yield the polarization of luminescence radiation by defect in solar cells.

Radiation emitted by the solar cell has a wave character that can interact with the silicon structures or hypothetically thin reflectance layer of solar cells. In our research we can observed the linear partially polarization luminescence light on poly-silicon crack defect. Spectral response of using CCD camera is approximately 300 to 1100 nm. Sinusoid dependence of luminescence intensity on the angle of linear polarization analyzer rotation shown this fact. The degree of polarization depends on the material, in this case the character of defect. Polarized light can be obtained in various ways. This fact opens up for potential next new questions in this widely course of study diagnostics defects silicon solar cells.

8825-1, Session 1

Degradation of transparent conductive oxides, and the beneficial role of interfacial layers

Heather M. Lemire, Kelly A. Peterson, Mona S. Breslau, Ina T. Martin, Kenneth D. Singer, Roger H. French, Case Western Reserve Univ. (United States)

Understanding transparent conducting oxide (TCO) degradation is critical to improving stability and lifetime of both organic and inorganic thin film PV modules, which utilize TCOs like indium tin oxide (ITO), aluminum-doped zinc oxide (AZO) and fluorine-doped tin oxide (FTO) as electrodes. These TCOs must retain their long-term functionality in diverse outdoor environments. In addition to bulk material degradation, interfacial degradation, a frequent avenue for failure in PV systems, is promoted by exposure to environmental stressors such as irradiance, heat and humidity. TCO samples were exposed to damp heat (85 °C, 85% relative humidity), ASTM G154, and modified ASTM G154 cycle 4 hot irradiance (70 °C, 1.55 W/m2 @ 340 nm) for up to 1000 hours. After each exposure, electrical and optical properties and surface energies of cleaned samples were determined. Yellowness, haze and resistivity of the TCO increased with exposure time, while the total surface energy decreased.

The delamination-vulnerable TCO/PV absorber interface can be engineered using interfacial layers to increase adhesion. We used allyltriethoxysilane (ATES) to modify the TCO/PV absorber interface, given its successful use in OLEDs. We characterized the electrical and optical properties, surface energies, and elemental composition of the silane on TCOs. Results demonstrate that silanization is a simple method of customizing the surface energy of the TCO, changing the water contact angle from 1° (clean ITO) to over 90° without compromising transparency or conductivity. Degradation data of TCO/silane stacks will be compared to open-faced TCO exposure results, as well as encapsulated outdoor results.

8825-2, Session 2

Predicting PV module service life *(Invited Paper)*

John H. Wohlgemuth, Sarah Kurtz, National Renewable Energy Lab. (United States); Tony Sample, European Commission Directorate-General Joint Research Ctr. (Italy); Masaaki Yamamichi, National Institute of Advanced Industrial Science and Technology (Japan)

Most PV customers want to know “if the PV modules purchased and deployed today will be able to survive for 25 years and how much they will degrade over that time”? We would like to be able to perform a set of accelerated stress tests that would determine whether a particular module type would survive for 25 years. Today we don’t know what set of tests to use. To help answer this question the PV industry created the International PV Module QA Task Force. The goals of the Task Force are to 1) Develop a QA rating system that provides comparative information about the relative durability of PV modules and 2) Create a guideline for factory inspections of the QA system used during PV module manufacturing. This presentation will discuss the QA Task Force program and the progress achieved over the first two years of the effort.

8825-3, Session 2

Characterization of defects in encapsulated solar modules using infrared lock-in thermography

Sergio Sánchez-Carballido, Juan Meléndez Sanchez, Fernando López Martinez, Emilio Olias, Univ. Carlos III de Madrid (Spain)

Infrared (IR) lock-in thermography (LIT) has been successfully used for defect detection in solar cells. Depending on the experimental setup, defects such as shunts, serial resistances, pre-breakdown regions, etc., can be qualitatively visualized or quantitatively measured. IR-LIT results improve the spatial resolution (SR) in defect visualization and the signal to noise ratio (SNR) between defects and sound regions as compared to the classic DC thermography. The same results have been accomplished on solar modules, considered as an ensemble of solar cells electrically connected. The main problem that appears in IR-LIT technique is the measurement when cells and modules are encapsulated, because most glasses used for encapsulation are opaque in the IR region. In this research the IR opacity of the encapsulating glass is treated from a thermal point of view. The solar cell has been considered as a heat source with a heating frequency actively generated by a modulated forward polarization. The encapsulation behaves as a thermal low pass filter, whose cutoff frequency has been calculated. In the experiments, a modulated forward electrical polarization has been applied to a solar module in the dark. The test sample has been a standard solar module of 36 cells connected in series. The thermal images have been acquired from the side of the external glass surface by an IR camera. A large improvement of SR and SNR has been demonstrated for shunt detection when the modulation frequency is below the cutoff.

8825-4, Session 2

Stress analysis of encapsulated solar cells by means of superposition of thermal and mechanical stresses

Sascha Dietrich, Matthias Pander, Matthias Ebert, Martin Sander, Jörg Bagdahn, Fraunhofer-Ctr. für Silizium-Photovoltaik (Germany)

Encapsulated solar cells are exposed to thermal and mechanical causing fracture, which may result in a power drop, arcing as well as hot spots in the long term. In order to minimize fracture of solar cells a fundamental understanding about the stress state is crucial.

Within this contribution mechanical stresses resulting from soldering, lamination, different operating temperatures (i.e. -30 – 75 °C) and mechanical loading are superposed, which is novel in PV science and engineering. The complex stress state in solar cells is calculated by means of finite element simulation. The generated simulation models include all details such as busbars and copper ribbons since they cannot be neglected in particular for interpreting the influence of thermal loads. A thorough analysis is given applying fundamental methods of material mechanics.

At first a systematic approach by means of uniaxial and biaxial bending is used in order to interpret the inhomogeneous multiaxial stress state of an encapsulated solar cell. This stress state has to be fully understood in order to deliver correct assumption for module design optimization and testing. Systematic studies of topology material parameters will be included in a second step. As a result generalized design measures will be given. E.g. the cell distance shall not fall below 3 mm due to strong interactions between the cells. Based on those and further definitions the stress state for a complete module will be analyzed and derivations for module design will be made in a third step.

8825-5, Session 2

Baseline testing procedures for PV modules beyond the qualification testing

Eric Schneller, Narendra S. Shiradkar, Neelkanth G. Dhere, Univ. of Central Florida (United States)

The qualification tests described in IEC 61215 for the c-Si PV modules are essentially pass/fail tests that assist in avoiding infant mortality. This paper reports on the baseline test procedure carried out on PV modules at Florida Solar Energy Center that go beyond the qualification tests and

obtain information about their degradation modes and mechanisms in the long run would allow prediction of their lifetime in various climates. The results from the baseline test procedures that have been carried out on mc-Si PV modules from three leading manufacturers are presented. Electroluminescence imaging has been used to detect and categorize the faults at the cell level. Indoor infrared imaging has been used to study the quality of electrical interconnects in the module. The infrared imaging carried out on the modules while they are undergoing outdoor exposure has provided information about the presence and distribution of hot spots in these modules. Conventionally, the insulation resistance tester has been used mostly for the dry and wet leakage test. In this study, several other tests such as Polarization Index test, Dielectric discharge test and Voltage excursion test are carried out on the PV modules. These tests have provided important information about the dielectric properties of module packaging materials that cannot be obtained using only dry/wet leakage tests. Finally a comparison of quality of Silicon cells, interconnects and dielectric/insulation properties of the packaging materials used in PV modules manufactured by the three leading manufacturers is presented.

8825-6, Session 2

Optical and electrical detection and localization of solar cell defects on microscale

Pavel ?karvada, Dinara Dallaeva, Elena Prokopyeva, Pavel Tomanek, Lubomír Grmela, Robert Macku, Brno Univ. of Technology (Czech Republic); Steve J. Smith, South Dakota School of Mines and Technology (United States)

Monocrystalline silicon wafer is still most used material for the fabrication of solar cells. The recent investigation shows that the quality of cells is often degraded by structural defects emerging during processing steps. On the other hand, there is a plenty of generally nonlocalized defects with different behavior and nature such as Schottky and ohmic shunts, edge shunts, cracks and dislocations there. Some of them are visible, other as microfractures, precipitates and other material structure inhomogeneities are often invisible. So a detection and localization of tiny local defects in the structure, as well as an assigning particular defects with corresponding degradation of photoelectrical parameters, is a key-point for solar cell reliability, lifetime and efficiency improvement. Although the breakdown can be evident in current-voltage plot, the localization of defects on the sample has to been done by microscopic investigations as well as by defects light emission measurement under electrical bias conditions.

Therefore modern scanning microscopy techniques are successfully applied in local diagnostics of defects in solar cells. The suggested method combines three measurements: electronic noise, local topography and locally induced photocurrent.

The experimental results obtained from samples where the defects were microscopically etched by focused ion beam are presented. Electrical and photoelectrical properties of sample before and after etching processing are also discussed.

8825-7, Session 3

UV aging and outdoor exposure correlation for EVA PV encapsulants *(Invited Paper)*

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A widely cited approximation in the solar industry is that "one week of xenon arc weather-o-meter exposure is equivalent to 1 year of field exposure." This statement is a generalization of test data generated in the mid 1990's as part of the NREL managed PVMaT-3 project. This approximation was based entirely upon yellowing of first generation EVA based encapsulants in two different accelerated test conditions, xenon arc and mirror accelerated outdoor aging. First generation EVA encapsulants were developed by STR under the JPL solar project 1975-1986 and are well known to exhibit yellowing (or browning) with exposure to UV and heat. This yellowing mechanism was understood and resolved with newer generation EVA encapsulation products introduced in late 1990's. Modules from the PVMaT-3 project included both older and newer generation encapsulants. Those modules were on a 2 axis tracker in Arizona from 1996 to 2012 and are now undergoing diagnostic tests. Older generation standard-cure encapsulant used in these modules exhibited severe browning over cells and the modules exhibit approximate power loss of 1% per year, but with very little drop of short circuit current (Isc). This same standard cure encapsulant material has been tested with updated xenon arc exposure methods and optical transmission tests to estimate the loss in power due only to browning and reduction in light transmission.

8825-8, Session 3

Examination of an optical transmittance test for PV encapsulation materials

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The optical transmittance of encapsulation materials is a key characteristic for their use in many types of photovoltaic (PV) modules. Changes in transmittance over time in the field affect module performance which may concern product warranties. Because transmittance is important in product development, module manufacturing, and field power production (both immediate and long-term), an international standard has recently been proposed by the Encapsulation Task-Group within the Working Group 2 (WG2) of the International Electrotechnical Commission (IEC) Technical Committee 82 (TC82) for the quantification of the optical performance of PV encapsulation materials. Existing standards, such as ASTM E903, are general and more appropriately applied to concentrated solar power than to PV. The solar-weighted transmittance of photon irradiance, yellowness index (which may be used in aging studies to assess durability), and ultraviolet (UV) cut-off wavelength may all be determined using the proposed standard. The details of the proposed test will be described and the results of a round-robin experiment conducted to validate the test procedure using representative materials will be presented. For example, the measurement requirements (wavelength range and resolution), the requirements for the spectrophotometer (including the integrating sphere and instrument accessories, such as a depolarizer), specimen requirements (choice of glass superstrate and substrate), and data analysis (relative to the light that may be used in the PV application) were actively explored by the Encapsulation Group. The round-robin experiment investigated both intra- and inter-laboratory instrument precision and bias for five encapsulation materials (encompassing a range of transmittance and haze-formation characteristics).

8825-9, Session 3

Factors causing adhesional strength deterioration and delamination in c-Si solar cells

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The dopant glass left on the c-Si cell has been known to cause

considerable loss of the adhesional strength and large-scale delamination after deployment of PV modules deployed in the harsh hot and humid coastal climate. It also caused a less severe loss of the adhesional strength and some delamination even after deployment of PV modules in the hot and dry climate. The acetic acid generated in modules using EVA encapsulant usually diffuses out through the back polymer sheet. However, in one incidence where the PV module composite was sealed with stainless steel back sheet the acetic acid generated by the EVA caused complete delamination of the EVA both from the c-Si cells as well as from the SS back sheet. There was a pungent smell of the acetic acid when the stainless steel back sheet was cut. An uneven application of the dopant can also cause large variation of dopant concentration. Significant loss of adhesion and even delamination were also observed in regions of the interfaces where high phosphorous concentrations had segregated due to chemically assisted diffusion. High concentrations of sodium from glass as well as from the coastal climate can also cause loss of adhesion and delamination. Reducing the sodium concentration in the glass combined with glass surface treatment have been found to minimize the loss of adhesion.

8825-10, Session 3

Weathering and durability of PV backsheets and impact on PV module performance

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Polymeric backsheets form the outer protective layer on the back of most crystalline and multi-crystalline silicon cell based photovoltaic modules. The mechanical, electrical, optical and chemical properties and durability of these backsheets are critical to the long term reliability, durability and safety of the photovoltaic modules. The stability of these backsheet properties is typically determined based on isolated stresses. However, impact of multiple stresses applied sequentially or simultaneously can lead to changes in materials properties that are more predictive of performance in the field. An important consideration in the development of accelerated test protocols is the level and duration of the stress. To test the weatherability of PV backsheets, key stresses include the sample temperature, light intensity and spectral power distribution and the presence and type of moisture applied. In this paper, we discuss performance of PV backsheets under these accelerated test conditions and compare changes in the materials properties to long-term outdoor performance of PV modules. We identify accelerated testing protocols that correlate with extended outdoor exposure, as well as accelerated test conditions that show no correlation with outdoor performance.

8825-11, Session 4

On differences between bathtub curves and linear degradation describing PV module degradation *(Invited Paper)*

Bolko von Roedern, von Roedern & Associates LLC (United States)

This addresses two separate issues that the human mind often confuses. The first is that not all PV module degradation data is fully and accurately interpreted. Second is the assumption that full and accurate data interpretation will necessarily lead to deeper insight and more accurate future predictions. It is however, not clear how much performance can be gained if secondary signals (like luminescence) are optimized. Often, these issues are reflected in data analyses that deal only with linear progressions, ignoring data that do not fit linear patterns. When claims are made that such data isn't public or does not exist with great enough accuracy, this may or may not reflect the real situation. While it may be instructive to understand PV losses in terms of per year (annual) loss, that might not accurately describe the actual degradation mechanism. A confusion may exists between average and individual numbers and greater accuracy and more data will not automatically guaranty deeper insight into an issue or allow more accurate future projections. The issue is whether or not more insight is gained by separation to identify the largest mechanism, or whether the correct combination of features minimizes degradation mechanisms.

8825-12, Session 4

Photovoltaic module lifetime and degradation science model development

Laura S. Bruckman, Nicholas R. Wheeler, Jiayang Sun, Roger H. French, Case Western Reserve Univ. (United States)

A better understanding of the degradation modes and rates for photovolatics (PV) modules is necessary to optimize and extend the lifetime of modules. Lifetime and degradation science (L&DS) is used to better understand degradation modes, mechanisms and rates of materials, components and systems in order to predict lifetime of PV modules. A PV module lifetime and degradation science (PVM L&DS) model was developed using statistical analysis including step analysis and structural equation models in order to elucidate statistically significant relationships between a variety of degradation modes and mechanisms. The PVM L&DS is an essential component to predict lifetime and mitigate the degradation of PV modules. Statistical analysis was used to explore the relationship of various module performance and degradation pathways from real-world and accelerated testing. The statistically signification relationships and significant model coefficients were then combined with domain analytics, incorporating materials science, chemistry and physics expertise, to produce a system of equations that model system performance based on unit degradation processes at the materials, component and system level. This exemplifies the development of a methodology to determine lifetime and degradation pathways present in modules and their effects on module performance over lifetime which can be iteratively refined.

8825-13, Session 4

Methods to evaluate the effect of water ingress: towards ultra-reliable PV modules *(Invited Paper)*

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A durable encapsulation scheme is of paramount importance to achieve high energy yields, a long lifetime and a high reliability of the solar modules. In the PV modules, the glass and polymeric materials act as (semi-permeable) barrier layers for moisture and environmental stresses and mechanically stabilize the modules. After the cell itself, the encapsulant represents the most important material in the module in term of module reliability. Indeed, a good material selection not only increases the module production but will directly impact on the module efficiency and durability. An in-depth research should be performed to understand and evaluate the durability behaviour of PV elements exposed to atmospheric conditions. At the module level, the properties of the encapsulation polymers, their interaction with the surfaces and the module layers, as well as moisture permeation are critical. In particular, for thin film technologies, transparent conductive oxides can be sensitive both to moisture and ion migration as can occur in outdoor conditions (1,2).

Water vapor is considered as one of the most important degradation factor acting directly on the polymeric materials and corroding the metallic and glass components. Moreover, these corrosion effects are increased by the formation of acetic acid mainly driven by moisture ingress (3,4).

In addition to corrosion effects, water vapor will directly affect the adhesion of the encapsulants to the glass and the other components of the PV-module leading to delamination failures (5).

Therefore, encapsulation materials need to be evaluated to clearly understand their interaction with water in order to establish their efficiency in protecting the PV device.

We will present here various methods contributing to understand failure modes related to water vapor ingress with the final goal of going towards new design for ultra-reliable PV modules (<30 years).

• Using 2D finite-element analysis in correlation with climatic data, a model is built to simulate water and acetic acid ingress within the module through the backside encapsulants (backsheet and EVA). A comparison between various climatic region and corresponding equivalent damp heat (DH) time is given.

• We describe a new design for compressive-shear testing of polymer layers bonded to rigid substrates. We use it to characterize real interfacial adhesion of different encapsulants to glass substrate before and after exposure to water vapor (DH).

(1) Steinhauser, Jérôme, et al. "Humid environment stability of low pressure chemical vapor deposited boron doped zinc oxide used as transparent electrodes in thin film silicon solar cells." Thin Solid Films 520.1 (2011): 558-562.

(2) Pélisset, Segolene., et al. "Monitoring water vapour penetration using a contactless technique." PVSEC, 2009.

(3) Köhl, Michael, et al. "Polymer Films in Photovoltaic Modules: Analysis and Modeling of Permeation Processes." Service Life Prediction of Polymeric Materials (2009): 361-371.

(4) Kempe, Michael D. "Modeling of rates of moisture ingress into photovoltaic modules." Solar energy materials and solar cells 90.16 (2006): 2720-2738.

(5) Chapuis, Valentin, et al. " Compressive.shear adhesion characterization of polyvinyl-butyral and ethylene-vinyl acetate at different curing times before and after exposure to damp-heat conditions", Prog.Photovolt.: Res. Appl. (2012).

8825-14, Session 4

Hot spot testing of PV modules

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Reverse bias hot spots are an important failure mode for PV modules. The present hot spot test in IEC 61215 edition 2 does a poor job of identifying and testing such hot spots. The methods used to identify the specific cells to test do not result in selection of the cells most likely to fail. In addition the test method does not result in identification of the worst casr shading condition for the selected cells.

A new hot spot test procedure has been developed and has been incorporated into the draft of the third edition of IEC 61215, In the new approach the cells within each module most likely to suffer from hot spot problems are identified. The test then specifies a method for determining the worst case shading for each of those identified cells.

While the proposed new test has advantages over the old test method, there are still several questions to be answered for the proposed method:

• Is the test procedure as written easy to follow?

• Does the proposed non-intrusive method of determining worst case shadowing really identify the condition where the shadowed cell is dissipating the most energy regardless of its shunt resistance?

• How long should the hot spot exposure be conducted and should the test be continuous or cyclic?

This paper will report on a set of experiments conducted to answer these questions about the new test method and will propose any necessary changes to the test procedure.

8825-15, Session 4

Finite element analysis based model to study the electric field distribution and leakage current in PV modules under high voltage bias

Narendra S. Shiradkar, Eric Schneller, Neelkanth G. Dhere, Univ. of Central Florida (United States)

The maximum system voltage for Photovoltaic systems is 600 V in US. Some modules are designed to operate even at 1500 V, which is the limit for IEC low voltage systems. The high voltage bias between the cell circuit and frame of the module leads to a leakage current flowing through the insulation of the module to the ground. Over time, this leakage current causes Electromigration of various species to and from the cell circuit, can result in slow degradation of the performance of PV module. It is important to understand the electric field distribution and leakage current pathways in the PV modules in order to study the system voltage induced degradation of PV modules. The leakage current from the PV modules deployed outdoor and under high voltage bias strongly varies with the environmental conditions. The lumped resistance models described in literature that attempt to explain the leakage current flow through the PV module do not provide adequate information about the distribution of leakage current through different layers of insulation present in the PV modules. In this paper, a Finite Element Analysis (FEA) based model for the insulation of PV module is described that yields useful information about the distribution of electric field, potential and leakage current flowing through different layers of module. The model is also used to predict and analyze the changes in leakage current with changing environmental conditions.

8825-16, Session 5

Development of an electrical calcium test for measuring very low water vapor transmission rates *(Invited Paper)*

Michael D. Kempe, Matthew O. Reese, Arrelaine A. Dameron, National Renewable Energy Lab. (United States)

Flexible thin-film PV is being explored as a way to reduce manufacturing and installation costs and improve power-to-weight ratios. These technologies are susceptible to moisture and require flexible, transparent barriers as an alternative to rigid glass. In order to achieve lifetimes of 25+ y, it is estimated that water vapor transmission rates (WVTR) at least as low as 1•10-4 g/m2/day must be achieved.

In this work, we have developed an electrical Ca (e-Ca) test method to quantify the WVTR of high performance barrier films. The barrier under test is adhered to a metal spacer with a variable size opening. The other side of the spacer is adhered to a test card with patterned Ca lines that function as sensors. By monitoring the resistance of Ca lines, as they are consumed by reaction with water, we can measure the barrier's WVTR. This method can measure dozens of samples in parallel, and it has been demonstrated to measure barriers in the 10-7 g/m2/day range. Considering that 1•10-4 g/m2/day will transmit a 1 µm layer of water over a 20 year period, if not accurately accounted for, the smallest uptake of water in any testing component can lead to erroneous results. Therefore, validation of any of these methods is an extraordinary challenge. Here we present results evaluating the sources of noise in this system and the limitations to the accuracy of this method looking at measurement accuracy and the sources and sinks for water within this method.

8825-17, Session 5

The reliability of bypass diodes in PV modules

Neelkanth G. Dhere, Narendra S. Shiradkar, Univ. of Central Florida (United States); Vivek S. Gade, Jabil Circuit, Inc. (United States)

The operating conditions of bypass diodes in PV modules deployed in the field are considerably harsher than the conditions at which the diode manufacturers test the diodes. This has resulted in several cases of field failures of bypass diodes and has raised concerns about the reliability of PV modules as a whole. The study of modes and mechanisms of the failures encountered in bypass diodes used in PV modules has a potential to provide important information which would be useful to predict the module lifetime. This paper presents the review of the failure modes and mechanisms observed in bypass diodes and current state of the work related to reliability testing of bypass diodes. The International PV Module Quality Assurance Task Force has recommended following four potential areas of research to understand the reliability issues of bypass diodes: Electrostatic Discharge, reverse bias thermal runaway testing, forward bias overheating and transition testing of forward bias to reverse bias. As a joint collaborative effort between Florida Solar Energy Center and Solar laboratory at Jabil Inc., laboratory testing of bypass diodes on the guidelines provided by the International PV Module Quality Assurance Task Force has been initiated. Preliminary results from this work will be presented.

8825-18, Session 5

Long term endurance test and contact degradation of CIGS solar cells

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is the most promising technology for thin-film solar cells with record efficiencies of 20,4% on laboratory scale and 17,8% aperture area efficiency on a 900cm? module. Another important factor besides the cell efficiency is the reliability and long term stability of the manufactured modules, which can be assessed by accelerated ageing.

In this contribution the accelerated ageing of CIGS mini modules has been investigated. Therefore, modules were dark annealed under dry heat conditions at different temperatures. During the endurance test a positive or negative bias was applied to the cells. In regular intervals the IV- and CV-characteristics were measured at room temperature. After an overall stress time of 3500h the IV-characteristics were determined under different illumination conditions (intensity, spectral illumination). Our previous publications suggest a barrier at the back contact to explain the observed parameter drifts. This contribution is focused on the influence of different bias conditions during the endurance test on the generation of a back diode and on the change of the net acceptor concentration. These parameter drifts have an impact on the open circuit voltage, fill factor and on the appearance of a cross over between dark and illuminated IV-characteristics. The interpretation of the observed parameter drifts was supported by SCAPS simulations based on the above mentioned back barrier model. As an outcome of the simulations signatures for the existence of a back barrier diode were established. IV-measurements, temperature dependent Voc measurements and SunsVoc measurements are helpful means to detect such back diodes.

8825-19, Session 5

Probabilistic design-for-reliability (PDfR) of photovoltaic modules (PVMs) *(Invited Paper)*

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Qualification testing (QT) is the major means for making a viable photovoltaic (PV) device into a reliable product. While the short-term goal of a particular manufacturer is to conduct and pass the established QT, the ultimate long-term goal of the solar industry as a whole is to make its deliverables reliable in the field. It is well known, however, that the today's PV modules that passed the existing QT often exhibit premature field failures. Are the existing QT specs adequate? Could they be improved to an extent that if the PV device, module or a system passed the QT, there is a quantifiable way to assure that its performance in the field will be satisfactory and that its projected lifetime will indeed take place? The application of the probabilistic design for reliability (PDfR) concept enables one to provide affirmative answers to this question. One effective way to do that is to conduct the appropriate failure-oriented accelerated testing (FOAT); carry out, on a wide scale, in addition to the well established FOAT models, predictive PDfR modeling to understand the physics of failure and predict the probability of failure (PoF) in the field; carry out sensitivity analyses to determine the variability of this probability and determine what should be changed to assure its acceptable level; revise the existing QT practices, procedures, and specifications; and master the PDfR methodologies, realizing that the PoF is never zero, but could be predicted, quantified, minimized, controlled, specified and even maintained at an acceptable level, using various prognostics and health monitoring (PHM) techniques and equipment.

8825-20, Session 5

Linking accelerated laboratory and outdoor exposure results for PV polymeric materials *(Invited Paper)*

Xiaohong Gu, Chiao-Chi Lin, Yongyan Pang, Jaonnie Chin, National Institute of Standards and Technology (United States)

Linking accelerated laboratory test to field performance for predicting the service life of PV polymeric materials are being investigated at NIST using the reliability-based methodology. In this study, the NIST SPHERE (Simulated Photodegradation via High Energy Radiant Exposure) was used for accelerated laboratory tests of numerous PV polymers and components, such as ethylene vinyl acetate (EVA), poly (methyl methacrylate) (PMMA), ionomers, fronsheet fluoropolymers, and backsheet materials. A factorial experiment was designed to evaluate the effects of temperature, relative humidity, and spectral ultraviolet (UV) irradiance, either applied individually or in combination, on the main degradation mechanisms of these materials. The outdoor exposure was carried out in Gaithersburg, Maryland. Multiscale chemical, optical, mechanical and morphological measurements were carried out to follow changes during accelerated and outdoor exposures. The results indicated that the effects of simultaneous multiple stresses on materials degradation closely depended on the polymer structure, composition and assembling (lamination vs. non-lamination). The UV radiation was the most important factor for the degradation of all studied materials. A synergistic effect was observed for several materials such as EVA, ionomer, and backsheets, but not for the frontsheet fluoropolymers when specimens exposed to a combination of both UV and high relative humidity. It was also found that a higher UV spectral intensity led to a higher degradation rate, but not the degradation mechanism for the studied PMMA. The implication of this work to the current test standards will be discussed.

8825-21, Session 5

Safety and performance analysis of a commercial photovoltaic installation

Babak T. Hamzavy, Alexander Z. Bradley, DuPont (United States)

Understanding how to optimize photovoltaic (PV) system performance over its life time is vital to the sustainable growth of solar. As the number

of installations and system size continues to grow, this understanding becomes increasingly important. A systematic understanding of degradation mechanisms that are induced as a result of variables such as the service environment, installation, module design, material, weather, operation & maintenance, and manufacturing is required for reliable operation throughout a system's lifetime. We report the results from an analysis of a commercial c-Si PV array owned and operated by DuPont. We assess the electrical performance of the modules by comparing the original manufacturers' performance data with the measurements obtained using a solar simulator to determine the degradation rate. This evaluation provides valuable PV system field experience and will document key issues regarding safety and performance. A review of the nondestructive and destructive analytical methods and characterization strategies that we have found useful for system, module, and subsequent material component evaluations will be presented. We provide an overview of our inspection protocol and subsequent control process to mitigate risk. The objective is to explore and develop best practice protocols regarding PV asset optimization and provide a rationale to reduce risk based on the analysis of our commercial installations.

8825-22, Session 5

A critical hurdle to widespread use of polymer based luminescent solar concentrators

Geoffrey B. Smith, Univ. of Technology, Sydney (Australia)

Luminescent solar concentrators have been studied and improved for over 30 years. Of all moderate gain solar concentrator systems they are fundamentally the most attractive from a range of geometric and optical perspectives for many solar cell materials, for daylighting via light guides, and for some bio-applications. Of most significance is their étendue advantages over mirror and lens systems in terms of best dealing with the diffuse component and varying beam directions of solar radiation. Despite this and some attempted commercial ventures they have yet to achieve their potential. This paper addresses what is for the dominant class of such concentrators, those involving fluorophore doped polymers, especially PMMA, a core residual problem. Their long-term stability outdoors is insufficient. This is not due to UV effects and dye quenching, which can be controlled, but to fast local photothermal interactions between the activated dye molecules and the host material. Production of char like nanoscale absorbers may result. These absorb over a broad-band and though very dilute lower output transport efficiency in practical sizes. Data which led to this conclusion is presented, plus possible solutions. Other improvements in LSC polymer technology only have practical value if this core problem is first mitigated.

8825-24, Session 6

Experimental analysis, simulation and design guideline to suppress moisture ingress into thin-film PV module under continuously varying environment

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Recently, encapsulants without sealing material are being considered, especially ionomer, as one of candidates for glass-to-glass PV module structure to lower material and manufacturing cost. In this work, permeation properties such as diffusion and solubility coefficients of encapsulant and sealing materials were investigated and experimentally determined. Permeation characteristics of different combinations of encapsulants and sealing materials are evaluated under different local weather conditions. Results from simulating the vapor transport through different combinations over an expected lifetime will be presented. Based on experimental and simulating results, design guidelines to minimize moisture ingress are suggested based on the choice of encapsulant and sealing materials for each weather condition.

8826-1, Session 1

Hyperdoping of semiconductors by pulsed laser melting: in pursuit of intermediate-band photovoltaics *(Invited Paper)*

Austin J. Akey, Christine B. Simmons, Joseph T. Sullivan, Jonathan Mailoa, Massachusetts Institute of Technology (United States); Daniel L. Recht, Harvard School of Engineering and Applied Sciences (United States); Michael J. Aziz, Harvard Univ. (United States); Tonio Buonassisi, Massachusetts Institute of Technology (United States)

Laser-assisted hyperdoping of semiconductors has the potential to create a new class of materials with an impurity band inside the host material's band gap. This impurity band would enable the utilization of sub-gap light, potentially improving the efficiency of photodetectors and photovoltaics while retaining the desirable properties of existing devices. Hyperdoping, realized using ion implantation followed by pulsed laser melting to rapidly resolidify the implanted region, allows dopants to be retained at concentrations well above the equilibrium solid solubility limit. We are pursuing an approach involving impurities and pairs of impurities with states deep inside the band gap that are expected to broaden into one or more impurity bands at very high concentrations. We will show evidence that boron and sulfur are retained at hyperdoping levels following co-implantation into silicon and pulsed laser melting, and that gold is retained at much higher levels than other transition metals. Investigations of the suitability of these materials for photovoltaic applications and the character of the intermediate bands formed will be discussed using quantitative metrics. The extension of the hyperdoping technique to other intermediate-band materials systems will also be presented.

8826-2, Session 1

New laser-based approaches to improve the passivation and rear contact quality in high efficiency crystalline silicon solar cells *(Invited Paper)*

Carlos Molpeceres, María Isabel Sánchez-Aniorte, David Munoz-Martin, Miguel Morales, Sara Lauzurica, Juan José García-Ballesteros, Univ. Politécnica de Madrid (Spain); Pablo Ortega, Isidro Martín, Mónica Colina, Cristóbal Voz, Gema López, Ana-Belén Morales, Ramón Alcubilla, Univ. Politècnica de Catalunya (Spain)

Laser processing has been the tool of choice last years to develop improved concepts in high efficiency (HE) crystalline silicon solar cells. Different approaches for emitter formation by means of laser-doping techniques, and the extensive application of laser-firing techniques for rear contact formation mainly on p-type substrates, has lead to a general acknowledgement about the dominant role of laser technology in the quest of industrially viable concepts for HE solar cell production. Nowadays, substantial efforts are underway to optimize these processes minimizing the induced damage in the material inherent to the laser irradiation process.

In this work we present two recent developments made by our groups to improve, using lasers, the passivation and contact quality on the rear side of two different concepts of high efficiency crystalline solar cells. In both cases we analyze in detail the influence of the laser irradiation parameters on the final contact quality. First, we discuss the possibility of using standard laser-firing techniques in heterojunction silicon solar cells in an approach fully compatible with the highly demanding low temperature processing concepts associated to these devices. Secondly, and bearing in mind that a real challenge in rear contact formation is to reduce the damage induced by the laser irradiation, we present a new strategy, in fact an evolution of the standard laser-firing approach, to contact the rear side of p-type c-Si solar cells by means of laser processing of dielectric stacks containing Al2O3 before rear metallization. This approach, less aggressive than the standard approach of irradiation after the rear metallization, is applied to 2?2 cm2 solar cells leading to photovoltaic conversion efficiencies well beyond 20% on 0.5 and 2.3 ? cm substrates.

8826-3, Session 1

Investigation of metal contacts for silicon solar cells using laser transferred 8 µm thick Al foils

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Laser transfer process for contact formation of silicon solar cells has been studied previously in our laboratory. The All-Laser-Transferred Contacts (ALTC) cell was demonstrated with initial efficiency of 15.1%. However, the thickness of laser transferred metal film was around 500 nm and was prepared by the vacuum evaporation process, which could increase the total series resistance. Also, the use of the vacuum evaporation process for preparing the coated glass increases the fabrication cost. Laser transfer of thick aluminum foil (8 µm) would lower the metal contact resistance and decrease the fabrication cost. A high-power nanosecond pulsed laser with wavelength of 1064 nm was used for laser transfer of aluminum foil. The initial demonstration was performed by laser transfer of aluminum foil through a passivation oxide (100 nm) layer to contact p-type silicon. The transfer of thick Al foil layer mounted on glass to Si substrate was carried out while Fraunhofer ISE group mounts the foil on Si substrate and fires it. We are able to laser transfer 8 micron thick Al foil with our current laser. With higher power laser, thicker foil could be transferred. Point and line metal contacts were investigated. The results of optical and scanning electron microscope images, contact resistance and electrical cell parameters will be reported. Studies are focused on the effect of laser transfer parameters on the optimization of cell performance.

8826-4, Session 1

Towards increased efficiency in solar energy harvesting via intermediate states *(Invited Paper)*

Eric Mazur, Kasey C. Phillips, Benjamin Franta, Yu-Ting Lin, Meng-Ju Sher, Harvard Univ. (United States)

Shining intense, ultrashort laser pulses on the surface of a crystalline silicon wafer drastically changes the optical, material and electronic properties of the wafer. The process has two effects: it structures the surface and incorporate dopants into the sample to a concentration highly exceeding the equilibrium solubility limit. This femtosecond laser "hyperdoping technique" enables the fabrication of defect- and bandgap engineered semiconductors, and laser texturing further enhances the optical density through excellent light trapping. Hyperdoped silicon opens the door for novel photodectors and for Earth-abundant, semiconductor-based solar energy harvesters with the potential for both low cost and high photoconversion efficiency.

The same technique can be used to form nanostructured and doped

TiO2 and non-stoichiometric TiN films. We show that oxygen, nitrogen, and chromium incorporation occurs in these films when the laser fluence exceeds the ablation threshold. Our research offers an innovative approach to alter the surface and structure of TiO2 to generate new materials with applications in visible-light watersplitting.

8826-5, Session 1

Role of process parameters on laser fired contact geometry and resistance

Ashwin S. Raghavan, Todd A. Palmer, Edward W. Reutzel, Tarasankar DebRoy, The Pennsylvania State Univ. (United States)

The evolution of the laser fired contact geometry of a silicon wafer with an aluminum metallization layer is studied using a transient numerical heat transfer and liquid metal flow model. This model considers time dependent alloy composition, the very large heat of fusion in aluminum-silicon alloys, and Marangoni convection of molten alloy driven by spatial gradients of temperature. The effects of laser processing parameters on the evolution of concentration fields produced are examined for a wide range of pulse durations and power densities during laser processing with various aluminum metallization layer thicknesses. The computed results of fusion zone geometry and concentration profiles are compared with the corresponding experimentally determined results. After the model is validated with experimental results, sensitivity of several laser parameters, such as the pulse duration, power, and power density, on the contact geometry and temperature and concentration profiles are examined.

8826-6, Session 1

Pulsed laser annealing of polycrystalline CdTe

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CdTe is an important photovoltaic material used in the majority of all thin film modules manufactured today. It has been shown that CdTe is an extremely stable material that is largely stoichiometric across a range of deposition techniques. Here, we show that pulsed laser annealing can be used to affect the stoichiometry of thin film CdTe. A KrF excimer laser with a wavelength of 248nm and pulse duration of 25ns is used to deliver various energy fluences between 0 and 200 mJ/cm2 to an unintentionally-doped polycrystalline CdTe film. The surface melting threshold is observed to be between 50-100 mJ/cm2 as evidenced by scanning electron microscopy and is seen to be confined only to the film surface. We show with x-ray diffraction that the structure of the bulk is largely unaffected by these treatments. To measure the stoichiometry at the surface we use x-ray photoemission spectroscopy while the bulk is measured with secondary ion mass spectrometry. The stoichiometry changes as a function of laser fluence over a depth of several microns even though the penetration depth of the 248nm excitation is <10nm. To help explain this, we present a full, 3D heat flow model which predicts temperatures vs. time and depth which helps us construct hypotheses which can align the seemingly disparate results from our work and the literature.

8826-8, Session 2

Solution based solar cells on flexible substrate assisted by laser *(Invited Paper)*

Seung Hwan Ko, KAIST (Korea, Republic of)

Laser processing of solution processed solar cell has attracted tremendous attention due to its economic and simple process nature. Solution process can remove expensive vacuum deposition processes and laser process can remove any high temperature processes. Thus, laser assisted solution process can fabricate solar cells on a heat sensitive polymer substrate. This kind of solar cells can be applied to light weight, low cost solar cells on plastic substrate and further can be fabricated by roll-to-roll process.

8826-9, Session 2

Comparison of two picosecond laser sources for SiNx ablation with subsequent nickel silicide formation by excimer laser annealing (ELA) for industrial high efficiency silicon solar cells

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The front side contacting of c-Si solar cells with a two-step nickel-copper (Ni-Cu) metallization requires local openings in the Anti-Reflective Coating (ARC) layer followed by the formation of a nickel silicide seed layer in the ARC trenches and subsequent metal plating. This work aims at correlating the nickel silicide formation by Excimer Laser Annealing of a thin PVD-Ni layer with the silicon surface properties resulting from ARC ablation. Using a ps-range laser source emitting at 532nm with a repetition rate of 200kHz, the first ablation process targets the selective removal of SiNx while inducing only slight changes to the surface topography and properties of an initial 100?/• n+ POCl3 emitter. The second ablation process involves a ps-range source emitting at 355nm with a repetition rate of 80MHz and targets the simultaneous formation of a selective emitter solar cell structure. Thermal effects induced by the 80MHz high cadency SiNx ablation process lead to a partial melting of the pyramids at textured silicon surface and a redistribution of the emitter profile. Nickel silicide formation in the ARC trenches resulting from the irradiation of a 50nm PVD-Ni layer with a XeCl Excimer laser (308nm, 150ns pulse duration) is investigated for each ablation process. After removal of the unreacted Ni using selective wet etch chemistry, the phase, thickness and uniformity of the nickel silicide is compared to a reference process where NixSiy is directly formed with same XeCl laser on textured silicon featuring same as-diffused 100?/• emitter. The influence of post-ablation surface topography and emitter properties is discussed. Both ablation processes target thin 20µm self-aligned NiSi line that can contribute to the industrial manufacturing of high efficiency silicon solar cells.

8826-10, Session 2

Optimal irradiance for sintering of inkjet-printed Ag electrodes with a 532 nm CW laser

Yoon Jae Moon, Heuiseok Kang, Kyungtae Kang, Jun Young Hwang, KITECH (Korea, Republic of); Seung Jae Moon, Hanyang Univ. (Korea, Republic of)

Industrial solar cell fabrication generally adopts printing process to deposit the front electrodes, which needs additional heat treatment after printing to enhance electrical conductivity. As a heating method, laser irradiation draws attention not only because of its special selectivity, but also because of its intense heating to achieve high electric conductivity which is essential to reduce ohmic loss of solar cells.

In this study, variation of electric conductivity was examined with laser irradiation having various beam intensity. 532 nm continuous wave (CW) laser was irradiated on inkjet-printed silver lines on glass substrate and electrical resistance was measured in situ during the irradiation. The results demonstrate that electric conductivity varies nonlinearly with laser intensity, having minimum specific resistance of 4.1 x 10-8 Ωm at 529 W/cm2 irradiation. The results is interesting because the specific resistance achieved by the present laser irradiation was about 1.8 times lower than the best value obtainable by oven heating, even though it was still higher by 2.5 times than that of bulk silver. It is also demonstrated that the irradiation time, needed to finish sintering process, decreases

with laser intensity. The numerical simulation of laser heating showed that the optimal heating temperature could be as high as 300 oC for laser sintering, while it was limited to 250 oC for oven sintering. The nonlinear response of sintering with heating intensity was discussed, based on the results of FESEM images and XRD analysis.

8826-11, Session 3

Pump-probe investigations and numerical simulation of the confined laser ablation of thin film systems used for photovoltaic *(Invited Paper)*

Heinz P. Huber, Jürgen Sotrop, Hochschule für Angewandte Wissenschaften München (Germany); Stephan Rapp, Technische Univ. München (Germany); Matthias Domke, Hochschule für Angewandte Wissenschaften München (Germany)

The transient behaviour of the laser lift-off of thin film systems, initiated by glass substrate side or by film side irradiation with a 660 fs laser pulse, is investigated from the femtosecond to the microsecond range. For this purpose, a pump-probe microscopy setup is utilized to measure the transient relative reflectivity change of the irradiated spot at the molybdenum/glass interface. Moreover, the setup enables to measure the dynamic mechanical movement of the film by interferometry. In addition, a multi-physics and multi-time scale simulation was performed to simulate the electron and lattice temperature, the phase transitions, and the mechanical movement of the film. The experiment and the simulated data suggest that the film bulging is mainly driven by a shock wave created by a volume expansion of about 10 % that occurs during the phase transition from solid to liquid. The acceleration of the removed thin films is in the order of 1010 m/s?. The films display a dome formation at a constant velocity of about 70 m/s. The mechanical motion continues for approximately 20 ns. Then intact disk or fractured film particles are sheared-off, if the tensile stress limit is exceeded.

8826-12, Session 3

Study of the laser scribing of molybdenum thin films fabricated using different deposition techniques

Neelkanth G. Dhere, Univ. of Central Florida (United States); Aravinda Kar, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Eric Schneller, Juliana Shimada, Florida Solar Energy Ctr. (United States)

Thin film solar cells, specifically CuIn1-xGaxSe2-ySy (CIGS) based devices, provide an alternative to Silicon based solar cells with the potential for lower production cost while maintaining comparable conversion efficiencies. In order to realize these lower production costs, the implementation of a monolithically integrated device is essential. Monolithic cell interconnections require three independent scribes commonly referred to as P1, P2 and P3. The P1 scribe is performed on the cell back contact and is required to electrically isolate adjacent cells. Molybdenum thin films remain the most suitable back contact for CIGS thin film solar cells, due to their high melting point and low reactivity. Laser scribing has been adopted for performing this scribe due to successful processing for a wide range of laser pulse lengths and wavelengths. This paper reports on the effect of the molybdenum thin film deposition technique, and the resulting film properties, on the characteristic of the laser scribe. Films were deposited using DC magnetron sputtering over a range of working gas pressures and powers as well as in single and multilayer configurations. It was found that the residual stress within the film led to significantly different laser ablation processes. This required independent tuning of the laser processing parameters to create a clean, defect free scribe for different samples. Experimentation was carried out using both film side and glass side processing. It was determined that processing these films from the glass side led to a reduction in cracks and delamination originating from the scribe. The processing conditions that produced successful scribe lines for the various films are presented and discussed.

8826-14, Session 3

Pulsed laser scribing of earth-abundant Cu2ZnSnS4 thin film solar cells

David J. S. Hwang, Di Liu, Stony Brook Univ. (United States); Makarand A. Karmarkar, Michael A. Scarpulla, The Univ. of Utah (United States)

No Abstract Available

8826-15, Session 4

Laser crystallization, sintering, and ablation for solar applications *(Invited Paper)*

Jungbin In, Sang-Gil Ryu, Daeho Lee, Sanghoon Ahn, Andy Cheng Zheng, Univ. of California, Berkeley (United States); David J. S. Hwang, Stony Brook Univ. (United States); Costas P. Grigoropoulos, Univ. of California, Berkeley (United States)

No Abstract Available

8826-16, Session 4

Beam shaping imaging system for laser microprocessing with scanning optics

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Laser beam shaping systems converting Gaussian to flattop or other irradiance profiles are used in various solar cell manufacturing laser technologies to enhance their performance. Scanning over whole working field with using popular 2- and 3-axis galvo mirror scanners is very often important part of microprocessing systems. Therefore, combining of beam shaping optics with scanning heads is an important technical task in field of solar cells manufacturing. As the beam shaping optics it is suggested to apply field mapping refractive beam shapers piShaper having some important features: low output divergence, high transmittance, extended depth of field, capability to work with TEM00 and multimode lasers, as result providing a freedom in building various optical systems. De-magnifying of flattop laser beam can be realized with using imaging technique; the imaging optical system to be composed from F-theta lens of scanning head and additional collimating system to be used right after a piShaper. One of the problems in this approach is implementation of compact design of the collimating part. As a solution it is suggested to apply a specially designed Beam Shaping Unit being based on piShaper and locating between a laser and a scanning head; the functions of that combined system are: conversion from Gaussian to flattop laser beam irradiance profile, compact collimator design, alignment features, easy adaptation to a laser and a scanning head used in particular equipment. There will be considered design features of refractive beam shapers piShaper and Beam Shaping Unit, examples of optical layouts to generate flattop laser spots, which sizes span from several tens of microns to millimetres. Examples of real implementations and results of material processing will be presented as well.

8826-17, Session 4

Laser drilling up to 15,000 holes/sec in silicon wafer for PV solar cells

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One way to realize a back contact solar cell design is to 'wrap' the front contacts to the backside of the cell [1]. This result in significantly reduced shadowing losses, possibility of simplified module assembly process and reduced resistance losses in the module; a combination of measures, which are ultimately expected to result in lower cost per watt of PV modules. A large number of micro-vias need to be drilled in a silicon wafer through which the front and rear contacts can be connected. Laser drilling was investigated using a pulsed disk laser was used which provided independent adjustment of pulse width, repetition rate and laser power. To achieve very high drilling rates, synchronization of laser beam with two-axis galvo scanner was established using a FPGA controller.

A design of experiments (DOE) was developed and executed to understand the key process drivers that impact the average hole size, hole taper angle, drilling rate and hole quality. Laser drilling tests were performed on wafers with different thicknesses between 120 µm and 190 µm. The primary process parameters included the average laser power, pulse length and pulse repetition rate. The impact of two laser spot sizes (34 µm and 80 µm) on the drilling results was compared.

The results show that the average hole size can be varied between 30 – 100 µm by changing processing parameters such as laser power, pulse length, repetition rate and spot size. In addition, this study shows the effect of such parameters on the hole taper angle, hole quality and drilling rate.

Using optimized settings, 15,000 holes per second are achieved for a 120 µm thick wafer with an average hole diameter of 40µm.

[1] K. Shizuo, W. Hiroyuki; Patent JP 58-039071, 1983

8826-18, Session 4

Rapid laser scanning based texturing of silicon surfaces for enhanced solar cell performance by improved light trapping

David J. S. Hwang, Matthew Quigley, Di Liu, Stony Brook Univ. (United States); Hee K. Park, Dong X. Yu, YUCO Optics Corp. (United States)

Extensive research in micro/nanoscale surface engineering has developed for many energy applications. The laser-texturing has proven to be a useful technique to improve solar light trapping performance in solar cell devices. However, state-of-the-art laser texturing methods still have limitation in realizing reasonable manufacturing cost and scalability. In addition, laser-textured surfaces are lack of nice structural connectivity with base material systems, frequently requiring subsequent chemical etching steps to overcome the addressed issues.

In this study, we will present recent evaluation results on a cost effective surface texturing method based on rapid scanning of nanosecond laser pulses. In contrast to conventional laser-assisted methods, we have achieved highly uniform and controllable texturing means over arbitrary scanning area on silicon surfaces. Detailed texturing mechanisms such as effect of unit laser spot size on the local thermo-capillary-driven textured structures, continuing texturing trend over the extended surface area, and effect of molten depth controlled by laser parameters, will be discussed based on advanced in-situ and ex-situ characterization techniques. It will be also shown that the resulting surface structures exhibit superior crystallinity assisted by simultaneous annealing mechanism in the course of rapid scanning of nanosecond laser pulses. The detailed effect will be visualized by experimental analysis using electron microscopes and optical microscope and spectroscopy. Finally, potential towards practical manufacturing capabilitiy will be considered in conjunction with reasonable manufacturing cost and scalability.

8826-19, Session 4

Optical and electrical properties of SnO2 thin films after ultra-short pulsed laser annealing

Davide Scorticati, Univ. Twente (Netherlands); Andrea Illiberi, TNO Science and Industry (Netherlands); Johann Z. P. Skolski, Univ. Twente (Netherlands) and M2i (Netherlands); Ton C. Bor, Wojciech Ogieglo, Michel Klein Gunnewiek, Aufried T. Lenferink, Cornelis Otto, G. R. B. E. Römer, Univ. Twente (Netherlands); Frank Grob, TNO Science and Industry (Netherlands); Dirk F. de Lange, Univ. Autónoma de San Luis Potosí (Mexico); Bert A. J. Huis in 't Veld, Univ. Twente (Netherlands) and TNO (Netherlands)

Ultra-short pulsed laser sources, with pulse durations in the ps and fs regime, are commonly exploited for cold ablation. However, operating ultra-short pulsed laser sources at fluence levels below the ablation threshold can be used for fast and selective thermal processing. This is especially advantageous for the processing of delicate thin films. A precise control of the heat affected zone (as small as tens of nanometers, depending on the material and laser parameters) can be achieved, thus enabling the treatment of the upper surface of thin films with negligible effects on the rest of the film and no thermal damage on sensitive substrates below. By applying picosecond laser pulses, the optical and electrical properties of a 900 nm thick SnO_2 film, grown by an industrial CVD process on boroflat-glass, were modified. The treated film showed a higher transmittance of light in the visible and near infra-red range, as well as slightly increased electrical sheet resistance. Changes in optical properties are attributed to thermal annealing, as well as to the occurrence of Laser-Induced Periodic Surface Structures (LIPSSs) on the surface of SnO_2 films. The latter were found to be superimposed on the morphology of the as deposited film. The increase of electrical resistance was attributed to the generation of laser induced defects during the fast heating-quenching cycle. These results can be used to further improve the performance of SnO_2-based electrodes for solar cells and/or electronic devices.

8827-1, Session 1

Topological optimization of nonlinear optical quantum wire networks *(Invited Paper)*

Richard Lytel, Shoresh Shafei, Mark G. Kuzyk, Washington State Univ. (United States)

Spatially extended molecular structures comprised of interconnected quantum wires are modeled as quantum graphs with one-dimensional electron dynamics. Their nonlinear optical responses can approach the fundamental limits for structures containing specific topological motifs. Graphs comprised of composites of star vertices exhibit the largest response, whereas an isolated closed-loop graph (ie, a molecular ring) has a small response regardless of the geometry (shape) of the loop. Combinations of loops with stars produce some of the largest nonlinearities ever predicted by any model and approach the potential optimization limits determined by the Thomas-Reiche-Kuhn sum rules for any quantum system.

We present the results of a comprehensive study of the topological dependence of the nonlinearities of quantum graphs and show exactly how first and second hyperpolarizability of a graph depend upon its topological class and how the hyperpolarizability tensors vary with graph geometry. We solve an arbitrary graph for its eigenvalues and eigenstates, use these to compute the complete set of transition moments, and employ a sum-on-states to get the hyperpolarizability tensor components. We invoke their rotation group properties to calculate the best shape for each ensemble member of thousands of random graphs with identical topology. We perform Monte Carlo calculations for loops, bent wires, stars, and combinations of these and show how graphs with stars share universal scaling behavior near the maximum nonlinear responses. We articulate a set of design rules for quantum-confined, quasi-one dimensional systems that may be realized using molecular elements and nanowires.

8827-2, Session 1

Optimizing hyperpolarizability through the configuration space of energy spectrum and transition strength spanned by power law potentials

Sean Mossman, Mark G. Kuzyk, Washington State Univ. (United States)

Our work seeks to determine what makes a large nonlinear response beyond the trivial strategy of making larger molecules. Various techniques have been applied to purportedly probing the full configuration space in hopes of finding the largest nonlinear-optical response. An important result of such studies: the off-resonant nonlinear optical response depends strongly on the nature of the energy spectrum and oscillator strength of the dominant transition. Given the persistent small gap between the best molecules and the calculated fundamental limit, speculations for the need of exotic and perhaps even unphysical Hamiltonians have been proposed.

Our approach is to focus on the class of power law potentials spanning many fundamentally interesting systems including hydrogen-like atoms, harmonic oscillator, particle in a box and electric multipoles -- systems that are analytically tractable. Smooth variation of the exponent covers all these classes as a subset of a much larger configuration space, providing the opportunity to characterize their nonlinear optical properties in terms of one parameter.

We focus on identifying universal properties associated with the largest first and second hyperpolarizabilities, including the nature of the energy spectrum and transition moments as the exponent is smoothly varied over the full domain. We find a discontinuity in the energy density spectrum for the exponent -2, a peculiar and fascinating potential known to have many bound states but no ground state. Our results will be related to measurable properties of real systems and the importance of the 1/x2 potential to nonlinear optics will be discussed.

8827-3, Session 1

From fundamental limits to quantum networks: a path from science to applications

Shoresh Shafei, Richard Lytel, Mark G. Kuzyk, Washington State Univ. (United States)

The theory of the fundamental limits of the first and second hyperpolarizabilities has taken us closer to understanding the major factors that determine the maximum attainable nonlinear-optical (NLO) response of molecular systems and discovering the properties required of a material to exhibit efficient nonlinear response. The goal is to apply this understanding to developing new approaches and strategies for designing structures with large nonlinearities that can be ultimately used in future technologies.

A comparison of this theory with experiments on many molecules reveals a large gap between the two. Efforts to understand the origin of the gap and finding new classes of materials with efficient nonlinear response have been based on Monte Carlo techniques that probe a large enough part of the configuration space to generate hypotheses. A class of systems that are amenable to such analysis is nonlinear optical quantum graphs, which can be viewed as artificial materials with controllable properties where a combination of confinement, geomerty and topology can lead to ultra large hyperpolarizabilities. Calculations of their hyperpolarizabilities already show values that approach the fundamental limit. Our present work focuses on extended our calculations to real systems such as quantum wires as the fundamental building blocks. To do so, we account for band structure on the nanoscale using Bloch's Theorem of many-particle wavefunctions, and calculate the hyperpolarizabilities, which can then be compared with experiment both in theory validation and in guiding the development of new materials.

8827-4, Session 1

Shape engineering to promote head-tail interactions of electro-optic chromophores

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Alignment of dipolar chromophores lies at the heart of organic electro-optic materials research. Among all the factors (e.g., external electric field, temperature, conductivity, etc.) affecting alignment efficiency or order parameter, interchromophore electrostatic interaction has been the focus of attention in the last decade. The strength of dipole interaction is highly dependent not only on dipole moment but also on chromophore shape and chromophore number density. Antiparallel interaction is dominant in the solid state of conventional EO chromophores (long and flat) and prevents electro-optic coefficient (r33) from scaling with chromophore concentration. Despite the great amount of research along various approaches to enhancing alignment, order parameters of organic EO materials are still low (0.13-0.2 v.s. 1 for a perfect alignment). Antiparallel interaction can be selectively attenuated by attaching bulky groups to the middle part of chromophore. However, it is synthetically

challenging to provide sufficient steric protection without causing severe reduction of chromophore concentration. In this paper, we will present the first realization of atom-economic steric protection of chromophore against H-aggregation in all directions and show evidences for the dominance of head-tail interaction over antiparallel interaction of a highly dipolar chromophore. With the novel shape, the EO coefficients of guest-host films of the chromophore do not show attenuation with increasing concentration up to 100 wt%. The dominance of head-tail interaction also enabled fabrication of optical quality thick films from the neat chromophore and allows poling induced alignment to retain at temperatures above the poling temperature – a phenomenon never observed for other chromophores.

8827-5, Session 1

Multilayer optical data storage by photobleaching of organic fluorophores *(Invited Paper)*

Cory W. Christenson, Brent M. Valle, Anuj Saini, Chris Ryan, Case Western Reserve Univ. (United States); Christoph Weder, Univ. de Fribourg (Switzerland); Joseph Lott, Univ. of Minnesota (United States); Eric Baer, Kenneth D. Singer, Jie Shan, Case Western Reserve Univ. (United States)

The capacity of optical data storage media has failed to keep up with magnetic media, limiting their application. This is mainly due to the inability to economically scale three dimensional optical media. We have recently reported optical data storage in 23 layers in a periodic bilayer polymeric film having 300nm thick writing layers separated by 3micron thick buffer layers at diffraction limited resolution using a 405 nm Blu-ray laser (Adv. Mater. 24 (38), 5222-6, 2012). The production of these films using a low-cost and highly scalable technique based on multilayer polymer co-extrusion promises large capacity optical data storage media up to the petabyte scale.

The writing process is based on photobleaching organic fluorophores incorporated as dopants into the active polymer layers. For example, 2.0 wt.% of the fluorescent chromophore 1,4-bis(?-cyano-4-octadecyloxystyryl)-2,5-dimethoxy-benzene (C18-RG) is doped into PETG, with PVDF buffer layers. We report here on investigations of the writing dynamics by pulsing a 405nm diode laser from 20ns durations and up. We find that both photochemical and thermal effects contribute to the photobleaching, with thermal effects and excited state absorption becoming dominant at higher powers. We interpret our results in terms of thermally activated rates and thermal diffusion. Photochemical processes are described by a multilevel model including both singlet and triplet manifolds, as well as ground state and excited state absorption. Different dyes and excitation wavelengths are also compared. Results are discussed in terms of the needs for long term optical data storage.

8827-6, Session 2

White fluorescent nano-fibers prepared by periodic organic hetero-epitaxy *(Invited Paper)*

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Para-hexaphenyl (p-6P) or ?-sexithiophene (6T) form crystalline organic nano-needles by epitaxial growth on various substrates [1,2]. It turned out that p-6P in combination with muscovite mica represents an outstanding material combination. In particular, the low substrate surface symmetry in combination with the resulting molecular alignment is the key to well ordered, parallel aligned nano-fibers providing highly polarized blue fluorescence and laser action [3].

To preserve the morphological properties of p-6P based nano-fibers and simultaneously tune their emission wavelength, periodic organic hetero-epitaxy was utilized. Multilayer structures of p-6P and 6T have been prepared by hot wall epitaxy and analyzed by AFM, fluorescence microscopy, UPS, XRD and time resolved spectroscopy.

We demonstrate that organic hetero-epitaxy can be applied to produce multilayered nano-fibers with high crystallinity, well defined epitaxial relationship along different material phases, molecular azimuthal order, and long-range morphological homogeneity. It could be shown, that it is possible to precisely control and tune the highly polarized PL emission of the nano-fibers from the blue to the green and orange spectral regime by a variation of the 6T concentration. Remarkably, it is possible to prepare nano-fibers emitting white polarized light. Furthermore, it was recently shown that such nano-structures are capable of laser emission in the green and orange spectral regime [4].

[1] C. Simbrunner et al., J. Am. Chem. Soc. 133 (2011) 3056

[2] G. Schwabegger et. al., Cryst. Growth Des. 13 (2013) 536

[3] F. Quochi, J. Opt. 12 (2010) 024003

[4] F. Quochi et al., Adv. Opt. Mat. (2013) in print

8827-7, Session 2

Waveguiding properties of individual electrospun polymer nanofibers

Yuya Ishii, Ryohei Kaminose, Mitsuo Fukuda, Toyohashi Univ. of Technology (Japan)

Optical circuits are needed to achieve high-speed, high-capacity information processing. An optical waveguide is an essential element in optical circuits. Electrospun polymer fibers have diameters in the nanometer range and high aspect ratios, so they are prime candidates for small waveguides. In this work, we fabricate uniform electrospun polymer nanofibers and characterize their optical waveguiding properties. Poly(methyl methacrylate) (PMMA) solutions of different concentration that contain a small amount of Nile Blue A perchlorate (NBA) are electrospun. Uniform PMMA/NBA fibers with an average diameter of 540 ± 60 nm are obtained from the 10 wt% solution. The fibers are covered with transparent cladding and their ends cut vertically. A laser beam with a wavelength of 533 nm is irradiated onto the fiber from the direction vertical to the fiber axis so it scans along the fiber. Photoluminescence (PL) spectra at the end face of individual fibers are then measured. The PL spectra exhibit a red shift as the distance (d) between the end face and irradiating point of the laser beam increases because of reabsorption of PL that is guided in the fiber. Measurements of five individual fibers reveal the PL intensity at the end face decreases with a ratio of ~10-?d where the loss coefficient (?) is 7.3–32 cm-1. In conclusion, we demonstrate optical waveguiding in electrospun single nanofibers and evaluate their ?.

8827-8, Session 2

Low loss photonic structures realised by solution processing at low temperatures

Andrew Strang, Imperial College London (United Kingdom); Manuela Russo, Imperial College London (United Kingdom) and ETH Zurich (Switzerland); Walter R. Caseri, ETH Zurich

(Switzerland); Donal D. C. Bradley, Imperial College London (United Kingdom); Natalie Stingelin-Stutzmann, Imperial College London (United Kingdom) and ETH Zurich (Switzerland); Paul N. Stavrinou, Imperial College London (United Kingdom)

Photonic structures that can be produced by solution processing are attracting increasing interest in the scientific and industrial community due to the advantages straight-forward procedures such as those adapted from bulk "plastic" manufacturing. Key for realising photonic structures from solution, and at low temperatures, is the development of versatile, high refractive index, low loss material systems. In this work we employ an organic/inorganic hybrid material that was developed by Russo et al. and is processable from an aqueous solution: titanium oxide hydrate cross-linked polyvinyl alcohol (PVA). The material's refractive index can be tuned from 1.5 to greater than 1.8, yet without inducing significant optical losses. The refractive index can be further increased to over 2.1 by thermal annealing, showing that the refractive index of these hybrids can be tuned over a similar window as the best materials previously reported, but without reducing the material's transparency. We attribute this highly beneficial feature of these novel materials to the fact that they are molecular hybrids rather than nanocomposites that suffer from nanoparticle aggregation even at relatively low loadings. As an initial demonstration of this material's use in photonic structures we present solution-processed distributed Bragg reflectors (DBRs), fabricated to a desired optical response, which achieve close to 100% reflectance over a pre-designed optical stop-band. We demonstrate experimentally and through modeling of such structures that the hybrid material exhibits unprecedentedly low optical losses and excellent interfacial quality when integrated in multilayer stacks using deposition techniques commonly employed in the manufacturing of commodity "plastic" products.

8827-9, Session 2

Straightforward electro-optic polymer/TiO2 waveguide modulators *(Invited Paper)*

Feng Qiu, Shiyoshi Yokoyama, Kyushu Univ. (Japan)

Electro-optic (EO) polymers and their devices have received considerable attention in the photonics applications. Based on Pockels effect in EO polymers, a variety of EO waveguide modulators have been realized, such as all polymeric modulators, hybrid sol-gel SiO2 / EO polymer modulators, and EO polymer / silicon slot modulators. An ideal EO modulator should possess high poling efficiency, low VπL, simple fabrication process and low propagation loss. In this work, we have presented a phase modulator and a ring-resonator modulator, both of which are based on an EO polymer/ TiO2 system. This system can be realized by a straightforward fabrication process, which consists of a sputtering, a photolithography, and two times spin-coating. The r33 of our EO polymer in the waveguide was improved to 120 pm/V due to the function of the TiO2 layer, which was 80% higher than that in a thin film. Combining high r33 and short interelectrode gap, the phase modulator had a low VπL of 4V?cm, corresponding to 2 V?cm in a push-pull MZI structure; the ring-resonator had an on/off ratio of 8dB, a Q-value of 4500, and a resonance peak shift of 1.5pm/V. In addition, the propagation losses were ~3dB/cm and ~1.8 dB/cm for the phase modulator and ring-resonator, respectively. The straightforward fabrication process, low VπL, and low propagation loss make our modulators suitable for industrial productions.

8827-12, Session 3

Multi-scale multi-material plasmonic composites for enhanced linear and nonlinear optical response *(Invited Paper)*

Pieter G. Kik, Seyfollah Toroghi, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Metal-organic and metal dielectric composites are well known to show optical properties that differ dramatically from those of their constituents. A new class of related composites, that of cascaded plasmonic metamaterials, has been predicted to produce field enhancement factors and nonlinear optical response which vastly exceeds that observed in systems. In these materials the coupling of surface plasmons on adjacent metal nanospheres with significantly different sizes can lead to effective multiplication of field enhancement factors. Thus far, research has focused on systems containing only a single material, and it is non-trivial how to extend this to more materials. Here we investigate the linear and nonlinear optical response of dielectric-Ag-Au composites containing Au and Ag nanospheres of different sizes in the 5 - 100 nm size range through numerical simulation. It is shown that careful engineering of inter-particle spacing and particle size differences enables the achievement of multiplicative cascading in these materials. The spherical nature of the metallic elements and their physical separation makes these structures ideal for high power applications. Internal field enhancement factors are shown to exceed those of isolated nanoparticles by over an order of magnitude. Effective enhancement factors for nonlinear optical absorption and refraction will be presented, and possible fabrication methods of these multiscale materials will be discussed.

8827-14, Session 3

Non-Markovian theory of collective plasmon-molecule excitations in nanojunctions combined with classical

electrodynamic simulations

Boris D. Fainberg, Holon Institute of Technology (Israel); Alexander J. White, Michael Galperin, Univ. of California, San Diego (United States); Boris Apter, Holon Institute of Technology (Israel)

Intersite dipolar energy-transfer interaction influences on electron transport through molecular wires in nanojunctions [1]. Such interactions can compensate Coulomb repulsions (CR) for particular relationships between their values [2]. This effect of exciton compensation of Coulomb blocking can be observed by varying the exciton coupling that can be achieved by controlling the plasmonic response of metallic contacts. Exploiting their tunability feature, wavelength specific designs for optimal energy transfer can be realized. We have applied the pseudoparticle nonequilibrium Green function formalism [3] to the study of coupling between plasmons and excitons in nonequilibrium molecular nanojunctions. The formalism treats on-site CR, inter-site exciton and plasmon-exciton couplings exactly, and is shown to be especially convenient for exploration of plasmonic absorption spectrum of nanopolaritonic systems with combined electron and energy transfers. We demonstrate the sensitivity of the exciton-plasmon Fano resonance to junction bias, CR and inter-site exciton coupling. We evaluate the local field and exciton coupling enhancement, along with the energy transfer to metal, using the dressed interaction [4] and FDTD calculations near plasmonic nanostructures. Our study opens a way to deal with nanopolaritonic systems in nonequilibrium molecular devices.

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8827-15, Session 3

Optical properties of nanopatterned light-emitting organic-inorganic composites and fibers

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Polymeric and nanocomposite micro- and nanostructures are widely exploited in different fields. Properly designing and combining their constituents is a direct and effective way to obtain new materials with tailored or improved properties. However, nanopatterning and interfacing nanostructures with devices at macro-scale remain challenging. Here we present a few model technologies that we developed, concerning the realization of light-emitting organic–inorganic composites gently shaped to obtain fluorescent nanostructures. Both in-situ and ex-situ nanocrystal synthesis approaches have been pursued and the optical properties of the resulting features have been investigated. We demonstrate line narrowing induced by amplified stimulated emission and assess the gain performances by the variable stripe length method.

8827-16, Session 3

Recent advances in two-photon 3D laser lithography with self-Q-switched Nd:YAG microchip lasers *(Invited Paper)*

Patrice L. Baldeck, Michel Bouriau, Prem Prabhakaran, Letitia Gredy, Olivier Stephan, Univ. de Grenoble, CNRS (France); Thomas Vergote, Hélène Chaumeil, Jean-Pierre Malval, Univ. de Haute Alsace (France); Chin-Te Lin, Ya Hsun Hsueh, Chao-Yuan Liu, Tien-Tung Chung, National Taiwan Univ. (Taiwan); Yi-Hsiung Lee, Chih-Lang Lin, Central Taiwan Univ. of Science and Technology (Taiwan)

No Abstract Available

8827-17, Session 3

Hybrid gold nanoparticles for fluorescent imaging and photodynamic therapy

Patrice L. Baldeck, Lab. Interdisciplinaire de Physique, CNRS, Univ. de Grenoble (France) and Lab. de Chimie, CNRS, Univ. Lyon (France)

We will review our work on hybrid Gold nanoparticles (GNP) that are coated with polymers bearing photoactive molecules optimised for their fluorescence or PDT activity. Our first goal in using GNP is to load a large density of photoactive molecules onto a biocompatible nanoplatform. Our second goal is to optimize the molecule GNP interaction to improve the photoactive properties.

In this project GNP have typical dimensions in the 50-100 nm that are suitable for in vivo imaging and therapy. Their geometrical shapes included spheres, rods, bipyramids and stars. The spherical shape is efficient only when a spacer is used to maintain a minimum distance between the photoactive molecule and the metallic surface. However, more elongated shapes, or tipped shapes can be used for a direct grafting of photoactive molecules if their transition dipole moments are maintained perpendicular to the surface (J-aggregate type of interaction between the GNP and molecules). We will report on optical spectroscopy, fluorescence imaging, cell uptake, cytotoxity, and PDT action of several type of polymers coatings and photoactive dye loading.

8827-18, Session 3

Recent advances in optical power limiting of nanoarchitectured materials

Jayan Thomas, Panit Chantharasupawong, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Optical properties of nanomaterials and nanostructured materials have gained significant research interest. For example plasmonic nanostructures and graphene optics were targets of several recent studies. Plasmonic materials have been extensively studied and used in various applications, for instance, bio-sensing, photovoltaic, and cancer treatments. Graphene materials, on the other hand, have been found to be promising in various applications due to its excellent electrical and optical properties. Recent advances in optical nonlinear properties of novel materials like nanoparticle and graphene oxide will be discussed. In the first part of the talk, the size dependence of optical nonlinearity, at the surface plasmon wavelength, in atomically engineered particles will be presented. Its potential application as a resilient optical limiting material will be discussed. It has been found by our group that functionalization of graphene oxides by means of fluorination can lead to improvement of their nonlinear optical properties. A well adopted technique for measuring nonlinear absorption of both solid and liquid samples is an open aperture Z-scan, which is a transmission based measurement. In the second part of the talk, we will present a measurement technique called OPAZ scan to perform optical Z-scan and photoacoustic Z-scan simultaneously in one experimental run. We have found that simultaneous measurement of the optical and photoacoustic Z-scan signals offers considerably better understanding of the mechanism responsible for the optical nonlinearity. Moreover, when these two sets of information are collected simultaneously, erroneous conclusions can be avoided. OPAZ scan enabled us to recognize the nonlinear processes within a mixture of nonlinear scattering species and nonlinear absorbers.

8827-19, Session 3

Hybrid nanostructured biocomposite for organic photonic

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Hydrotalcite-like (HTlc) compounds are layered solids with peculiar physical and chemical properties given their structural anisotropy. The intercalation of guest species possessing chromophoric groups into host layered nanoparticles gives rise to nanostructured materials with photophysical properties which are strongly affected by the geometrical and chemical environment experienced by the dye [1].

In particular, organic conjugated small-molecules are well-indicated candidates for the functionalization of HTlcs given their interesting optical and photonic properties, such as efficient optically pumped lasing in the solid state.

Natural biopolymers recently emerged as a highly promising candidates for realizing biocompatible photonic components. Indeed, we have recently demonstrated that dye-doped silk thin films can be implemented for organic lasing onto nanostructured grating, thus opening new perspectives for the applications of optically active silk in biophotonics and organic optoelectronics [2].

Here, we present the heterogenization of a chromophore with lasing properties on inorganic lamellar nanoparticles when dispersed in biopolymers. We report on the photonic properties of the new functionalized nanocomposite once deposited onto optical active substrates. A detailed photoluminescence time-resolved spectroscopic investigation is carried out for determining the specific photophysical processes and dye localization within the hybrid organic-inorganic nanostructures.

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[2] Toffanin S. et al., Appl. Phys. Lett. 2012, 101, 091110.

8827-20, Session 3

Fabrication of high Q-cavities with functional polymer cladding

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No Abstract Available

8827-10, Session PWed

The performance analysis of an electro-optic polymer modulator

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In this paper, we present a detailed analysis about the electro-optic (EO) polymer modulators using a full vectorial finite difference (FVFD) mode solver for an optical waveguide and a finite-element method (FEM) for a microwave electrode. A detailed discussion has been presented to describe a modulator about performance parameters: Vpai L, ?fL, Nm, ?c and zc with the design parameters, where VpaiL is the product of the half-wave voltage Vpai and the electrode interaction length L, the parameter ?fL is the product of the 3 dB optical bandwidth ?f ?and the electrode interaction length L, ?c is the conductor loss and Zc is the characteristic impedance.

8827-11, Session PWed

Design of Mach-Zehnder interference modulators composed of enhanced electro-optic active polymers *(Invited Paper)*

Guangming Xu, Jialei Liu, Zhen Zhen, Xinhou Liu, Technical Institute of Physics and Chemistry (China)

Organic electro-optic polymer has relatively low dielectric constant and especially high electro-optic coefficient, which is one of the perfect materials for making modulators with low loss and high bandwidth. In this paper, we firstly synthesized a novel chromophore based on 4-(diethylamino) salicylaldehyde, which was used as an electron donor and had one reactive site to introduce rigid isolated benzyl group. Polymers doped with the innovative chormophore showed good thermal stability and high electro-optic activity, which were adopted as core materials and used to design Mach-Zehnder interference (MZI) modulator. In the second part of the paper, we combined cladding materials and core materials and designed a low loss MZI optical waveguide. We used tapered waveguides at the input and output ports of MZI to reduce the coupling loss with fibers and tapered multimode Y-branches to equally split or combine optical signals. By simulating the transmission of optical modes in tapered structures, we calculated the optical loss of MZI waveguides and optimized the waveguides structures. Finally, we respectively designed the modulators with 50GHz 3dB bandwidth using the coplanar waveguide electrodes (CPWE) and the micro-strip electrodes (MSE), which are two typical traveling wave electrodes in microwave applications. We detailed analyzed the influence of electrodes structures on the microwave response and compared the CPWE and MSE when applied to polymer modulators. Fabrication of the modulators is under development. Modulators made of organic electro-optic polymers have great application prospects in the fields of information procession and communication needing high speed and high bandwidth.

8827-13, Session PWed

Photoluminescence characteristics of dye-doped polymer nanofibers excited by surface plasmon polaritons

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One-dimensional nanostructures are attracting considerable attention because of their subwavelength size and unique optical properties including light confinement, guiding, and amplification. Electrospinning is a simple and versatile technique to produce polymeric fibers with diameters in the nanometer range, and allows light-emitting nanofibers to be prepared simply by adding organic dyes to raw polymer solutions (Y. Ishii and H. Murata, J. Mater. Chem. 22, 4695 (2012)). The photoluminescence (PL) of such fibers excited with external light sources has been thoroughly investigated, but PL arising from surface plasmon polariton (SPP) excitation has not been reported. In this work, we use SPPs to excite dye-doped electrospun polymer nanofibers by attenuated total reflectance. Uniform electrospun polymer nanofibers composed of poly(methyl methacrylate) (PMMA) and Nile blue A (NBA) with an average diameter of 540 ± 60 nm are prepared. The PMMA/NBA fibers are placed on an Au thin film deposited on a semi-cylindrical prism. A laser beam with a wavelength of 633 nm is then irradiated onto the Au film with different incident angles (?), and PL from the fibers and reflectance are measured. The highest intensity PL is obtained at ?=44°, where reflectance showed its minimum value because of excitation of SPPs. Our results confirm that SPPs can excite dye-doped electrospun polymer nanofibers.

8827-21, Session PWed

Design considerations for monolithic beam formers based on electro-optic polymer phase modulators and strain-induced optical waveguides

Richard S. Kim, Attila A. Szep, Nicholas G. Usechak, Air Force Research Lab. (United States)

The fabrication and characterization of a 1?4-element integrated beam former based on electro-optic (EO) polymer phase modulators (PM) is summarized including findings related to waveguide loss, near- and far-field diffraction patterns, and the maximum steering angle achievable. Based on this device, two alternate designs are proposed to improve performance: an unequally spaced 1?4-element and an equally spaced 1?8-element beam former both based on EO polymer PMs. Models of these alternative designs indicate that waveguide propagation loss and strong grating lobes, both of which degraded the performance of the initial device, can be substantially improved. The proposed approach explored by the 8-element beam former introduces novel components including strain-induced optical waveguides, hybrid integration of active and passive polymers, modified waveguide diffraction aperture, and directional coupler thermo-optic (TO) switches.

8827-22, Session PWed

Investigation of third order nonlinear optical properties in s-indacene-1,3,5,7(2H,6H)-tetraone based D-pi-A-pi-D chromophores by z-scan

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Recently there has been much interest in two photon absorbing chromophores for two photon initiated polymerisation1and reversible multistage redox systems.2 Centro-symmetric D-π -A-π -D chromophores also have potential in photonic applications such as optical communication and switching, due to their third-order optical nonlinearity.3 Variations can be made to the donor, the acceptor and the conjugated spacer such that it is possible to fine tune the electronic structure of the chromophore for particular applications4 and this enables the development of smart materials.

Here we describe the synthesis and characterization of a novel range of symmetrical two photon absorbing dyes based on a D-π -A-π -D architecture utilizing s-indacene-1,3,5,7(2H,6H)-tetraone based acceptors. Dialkyl-aniline based donors were synthesized and the effect of conjugation length on the optical properties of the chromophores was investigated in an effort to tailor these materials for photonic applications. Conjugated linkers containing thiophene and pyrrole moieties were investigated. The third order nonlinear optical properties of these materials were investigated by z-scan. We report our z-scan data, which shows these materials have high third order optic nonlinearity. The ability to tune the nonlinear optical properties by varying the structure of the molecules is also discussed.

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(4) Ma, X.; Ma, F.; Zhao, Z.; Song, N.; Zhang, J. Synthesis and properties of NLO chromophores with fine-tuned gradient electronic structures. Journal of Materials Chemistry 2009, 19, 2975.

8827-23, Session PWed

Surface-emitting liquid crystal laser using nanostructured, transparent, and conductive films

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An organic dye laser has received considerable attention because of a broad and continuous tunability in the visible region, an intrinsic low threshold, and an easy processing. Particularly, a distributed feedback (DFB) structure is one of the preferred resonators to achieve such organic lasers. For a given period of the DFB grating, the second-order diffracted light makes a counter-propagating mode, resulting in optical feedback for lasing action. Lasing can be out-coupled to the surface normal direction by first-order Bragg diffraction.

Indium-tin-oxide (ITO) films have been widely used as transparent conducting electrodes of optoelectronic devices such as displays and solar cells due to high optical transmission and good electrical conductivity. Recently, we fabricated ITO films with one-dimensional periodic nanostructures by all-solution processing of ITO nanoparticles and a nanoimprint lithography (NIL) method. The NIL used in this study is a promising technique for quick, simple, and low-cost surface patterning with submicron resolution. The experimental transmission spectra from the nanostructured ITO films with various periodicities showed specific transmission dips due to light diffractions. Here, we use this nanostructured ITO film as a DFB resonator, transparent electrode, and alignment layer of nematic liquid crystals. Dye-doped nematic liquid crystals are introduced into the DFB resonator. In addition, the electro-optic performance of the lasing device based on nanostructured ITO electrodes is demonstrated successfully. The present lasing device provides various opportunities in photonic device application and its simple fabrication process can be readily used for large area geometries from the viewpoint of practical application.

8827-24, Session PWed

Determination of refraction nonlinear index, for effect thermal, of solutions with nanoparticles of gold

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The research of nonlinear optical properties of materials for the manufacturing of opto-electronic devices, had a great growth in the last years. The solutions with metal nanoparticle present nonlinear optical properties. In this work we present the results of characterizing, analyzing and determining the magnitude and sign of the nonlinear refractive index, using the z-scan technique in solutions with nanoparticles of gold, lipoic acid and sodium chloride. We studied 5 different solutions. We used a continuous Argon laser at 514 nm with variable power, a lens of 18 cm and a chopper. Three different power of laser and two frecuencies of chooper were used to analize the five solutions. We studied how the presence of lipoic acid and sodium chloride modified the nonlinear optical properties of the Au-nanoparticles solution in water. We determined the nonlinear refractive index in each case and we found it was in the order of 10 E-7. These materials have potential applications mainly as optical limiters.

8827-25, Session PWed

Effects of energy offsets and molecular packing on exciton and charge carrier dynamics in small-molecule donor-acceptor composites

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Understanding of exciton and charge carrier dynamics in organic donor-acceptor (D/A) heterojunctions is important for development of organic solar cells, light-emitting diodes, and photorefractive applications. Thus far, most effort has been directed towards studies of D/A materials with polymer donors and fullerene acceptors, while small-molecule D/A bulk heterojunctions (SMBHJ) remained relatively unexplored. We present a study of SMBHJs based on high-performance solution-processable functionalized fluorinated anthradithiophene (ADT-R-F) and pentacene (Pn-R-F8) derivatives. Here R is a side group which dictates molecular packing in the solid state without affecting optical and electrochemical properties of molecules themselves. We chose one of the ADT derivatives, ADT-TES-F, which exhibits a 2D pi-stacking “brickwork” packing, as the donor, and ADT-TIPS-F (2D “brickwork”), ADT-TSBS-F (1D “sandwich-herringbone”), Pn-TIPS-F8 (2D “brickwork”), and Pn-TCHS-F8 (1D “sandwich-herringbone”), as acceptors. We measured photoluminescence (PL) and photoconductivity, at time scales from sub-nanoseconds to many seconds after photoexcitation, at various acceptor concentrations, under various experimental conditions. This enabled us to establish effects of (i) LUMO energy offset between the D and A molecules and (ii) molecular packing at the D/A interface and in the acceptor domains on exciton and charge carrier dynamics. Differences in molecular arrangement in the acceptor domains both in ADT/ADT and ADT/Pn D/A composites resulted in pronounced differences in charge carrier photogeneration and recombination dynamics. In ADT/Pn D/A composites, exciplex formation at D/A interfaces was observed; exciplex contribution to the overall PL and photocurrent was determined to depend on the D/A distance, which is affected by the side-group R of Pn acceptors.

8827-26, Session PWed

Phase-shifted gratings in azo doped polymers and their analysis by coupled-wave theory

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Phase (index) grating inscription in azo-dye doped polymers is an interesting phenomenon because of its high diffraction performance and applicability to real-time 3D displays.[1,2] Although several these materials investigated in preceding studies worked without external electric field in symmetric optical alignments, some of them showed an asymmetric phase shift of periodic modulation of refractive index from the interference fringe formed by irradiation beams, resulting in energy exchange between two coupled beams. The mechanism of the behavior was usually attributed to the molecular motions triggered by trans-cis isomerization, but their details were still unknown. Therefore, experiments on temporal evolution of the process and their translation into physical meaning are necessary.

In order to investigate the evolution of grating inscription and phase shift, several methods have been developed. In this study, we analyzed the coupled wave equations proposed by Kogelnik, and derived general solution applicable to both phase and amplitude gratings with arbitrary phase relationship. We showed that the analysis based on the equation can give a direct evidence of the phase shift between the phase and amplitude gratings if it exists.

This method was applied to the fringe pattern inscribed in thick films of PMMA doped with an azo-carbazole dye, NACzEtOH and its derivatives, and was compared with other experimental results obtained by conventional means.

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8827-27, Session PWed

Optical fiber waveguides using DNA-based solutions as core materials

Bjorn Paulson, Woohyun Jung, Tavakol N. Baresari, Kyunghwan K. Oh, Yonsei Univ. (Korea, Republic of)

We present spectral analyses of optical fiber waveguides containing DNA-based solutions as the optical core material, as well as separately measured optical dispersion curves for said solutions. DNA-lipid biopolymers have shown a high refractive index and potential for amplifying the optical nonlinearity of certain nonlinear optical dyes when used in solid thin-films and in gel-cuvette waveguides. Here we demonstrate the optical potential of DNA and DNA-lipid biopolymers in solution. Using an Abbe refractometer and CW light sources, we measure the visible (complex) refractive indices of high-refractive-index and low-viscosity DNA-based solutions, including DNA-toluene solution, DNA complexed with cetyltrimethylammonium (DNA-CTMA) in n-butanol, DNA-CTMA-ethanol solution, and DNA-CTMA-hexafluoroisopropanol solutions. Refractive indices are presented for several length distributions of DNA, at several concentrations. We also demonstrate DNA-based solutions in their liquid form as the core for optical fiber waveguides, with the silica glass of the optical fiber serving as a cladding, and the light guided down the DNA-based liquid core such that there is high biopolymer-light interaction. The waveguides used are a step-index waveguide based on a filled hollow optical fiber and a liquid-filled photonic crystal fiber, with their transmission spectra measured by optical spectrum analyzer.

8827-28, Session PWed

Nonlinear optical properties of DNA and betanin natural dye doped silica sol-gel glasses

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Sol-gel process is a technique for developing amorphous or crystalline materials from a liquid phase at room temperature. It involves the formation of inorganic oxides from silicon - alkoxide with addition of a solvent and catalyst undergoes hydrolysis followed by polycondensation resulting in a final product in the form of glass or crystalline material that can be casted as a thin film. The specific research for non-linear optical materials prepared by sol-gel technology has been achieved by the preparation of semiconductor nanoparticle such as CdS, CdSe, CdTe, CuCl, CuBr, Bi2S3 and PbI2, metal nanoparticle and organic dyes doped glasses. The third order susceptibilities of these materials are quite high and depend on the concentration of the dopant.

In the present work we prepared silica sol-gel glass doped with DNA and betanin dye and studied the nonlinear optical absorption using a single beam open aperture Z-scan method. A Q-switched Nd: YAG laser (Spectra PhysicsLAB-1760, 532 nm, 7 ns, 10 Hz) was used as the light source. A 20 cm converging lens was used to focus the laser beam. Using a translation stage attached to a stepper motor the sample was moved in a spatially varying intensity region on either side of the focal point. The incident and transmitted energies can be measured simultaneously using two probe heads of the energy ratio meter. Reverse saturable absorption (RSA) at 532nm is observed for DNA and saturable absorption (SA) for betanin dye. In DNA-betanin doped system, by increasing the concentration of DNA, SA behavior of betanin dye is switch to RSA. And also observed that by increasing the input laser power density SA behavior of betanin dye switched over to RSA.

8827-29, Session PWed

Shape and morphology tuning of p-phenylenediacetonitrile-based fluorescent nanoparticles

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Fluorescent organic nanoparticles (FONs) consist of specific molecules capable of inhibiting fluorescence concentration quenching while causing aggregation-induced emission due to suppressed intramolecular torsions, which are usually accompanied by intramolecular planarization and/or specific head-to-tail molecular arrangements in the aggregates. A special attention to the FONs is paid for their potential applications in solid-state light emitters, fluorescent labels and sensors [1,2].

In this work, formation of the p-phenylenediacetonitrile-based FONs as well as their properties were studied systematically as a function of different alkyl and aryl side-groups linked to the molecule backbone. The FONs were formed by a simple reprecipitation method in the tetrahydrofuran(solvent)/water(non-solvent) mixtures at different solvent/non-solvent ratios, from 1:0 to 1:49. Dynamic light scattering and electron microscopy results demonstrated the possibility to tune FON sizes from 50 up to 1000 nm, whereas fluorescence quantum efficiency and optical spectroscopy measurements indicated the possibility to vary emission efficiency by a couple orders of magnitude, and moreover, alter shape and morphology of the nanoparticles in a controlled manner. Particularly, the selected p-phenylenediacetonitrile compounds bearing long alkyl side-moieties were shown to form highly-fluorescent crystalline one-dimensional nanowires and weakly-fluorescent amorphous spherical nanoparticles just by slightly tuning solvent to non-solvent ratio in the tetrahydrofuran/water mixture. The influence of different side-groups on the phenylenediacetonitrile molecule packing in the FONs and their fluorescence turn-on behavior is discussed.

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8827-30, Session PWed

Fabrication and characteristics of thin-film waveguides based on DNA biomaterials

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In the development of optoelectronic devices, deoxyribonucleic acid (DNA) has been a representative material which has received much recent attention as a promising research area. We constructed thin-film waveguides based on DNA-Biopolymer materials and DNA monolayers grown by a self-assembly process. Using solid state DNA-CTMA as a core, and PDMS as cladding, we manufactured and measured the spectral profile of slab waveguides using CW light sources, including thermo-optic coefficients and birefringence. We also report on an optical phenomenon of DNA monolayers grown by a self-assembly process. Discrete 2D nanocrystal structures of DNA were prepared on a light-guiding substrate. The high evanescent field interaction between the guided light supplied via optical fiber and DNA monolayers enabled the systematic investigating of the optical properties of DNA nanocrystal structures. In particular, light guided down the fiber and received by an optical spectrum analyser enabled spectral analysis, while morphology studies of the self-assembly DNA were performed by atomic force microscopy. We expect that biomaterials such as DNA-lipid complexes will have a unique application in optical devices compared with traditional fossil fuel-based polymers.

8827-31, Session PWed

Synthesis and characterization of ring-protected electro-optic chromophores

Lianjie Zhang, Jianyuan Sun, Logan P. Sanow, Cheng Zhang, South Dakota State Univ. (United States)

Antiparallel interaction among dipolar chromophores is the dominant force in the solid state of conventional EO chromophores (long and flat). This interaction is responsible for the formation of acentric aggregates and prevents electro-optic coefficient (r33) from scaling with chromophore concentration. Antiparallel interaction can be selectively attenuated by attaching bulky groups to the middle part of chromophore. However, it is synthetically challenging to provide sufficient steric protection without causing severe reduction of chromophore concentration. In this paper, we will present the synthesis and characterization of atom-economic ring protection of chromophores against H-aggregation in all directions and show the effect of ring protection on optical properties of the chromophores in solution and film.

8827-32, Session PWed

Synthesis and electro-optic properties of the chromophore-containing NLO polyarylate polymers

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Base on the same two monomers, diphenolic acid (DPA) and isophthaloyl chloride (IPC), three chromophore-containing nonlinear optical (NLO) polyarylate polymers were prepared. A tricyanofuran (TCF)-acceptor type chromophore group was in main-chain (mPAR-chr1), side-chain (sPAR-chr1) and side-chain with a 1,1-bis(4-hydroxyphenyl)-1-phenyl-2,2,2-trifluoroethane (BPAPF) group (sPAR-F-chr1), respectively. The obtained polymers were characterized and evaluated by UV-Vis, 1H NMR, DSC and TGA. The polymer mPAR-chr1 and sPAR-F-chr1 showed excellent film forming ability. All the polymers exhibited good electro-optic (EO) activity. The relationship between EO coefficients (r33) and the chromophore concentration of the three polymers were also characterized and discussed. There were no obvious differences found in EO activity between mPAR-chr1 and (sPAR-chr1) polyarylates with the same chromophore. The fluorinated block polyarylate sPAR-F-chr1 has the largest r33 value in these three polyarylates which is 52 pm/V at the wavelength of 1310 nm (which is almost twice the r33 value of normal polymers contained the same chormophore at the same content), when the concentration of chromophore 1 is 18wt.%. 85% of the r33 value was retained in the sPAR-F-chr1 after being heated at 85oC for 600 hours. The polymer sPAR-F-chr1, with good solubility, high Tg (above 200 oC) and side functional group at the same time, may probably be a practical NLO material.

8827-33, Session PWed

Effects of molecular charge density polarization on chi(1) and chi(2): a computational study of 2-methyl-4-nitroaniline (MNA) and 4-(N,N-dimethylamino)-3-acetamidonitrobenzene (DAN)

Tomasz Seidler, Jagiellonian Univ. in Krakow (Poland) and Univ. of Namur (Belgium); Katarzyna Stadnicka, Jagiellonian Univ. in Krakow (Poland); Benoît Champagne, Univ. of Namur (Belgium)

Molecular crystals are materials with prospective second-order NLO properties. Their design faces the problem of optimum molecular alignment in the crystal structure. Among these, the prototypical MNA and DAN, which crystallize in non-centrosymmetric space-groups owing to molecular asymmetry have been characterized using experimental and theoretical approaches.

When applying the Rigorous Local Field Theory developed by Hurst & Munn[1] the chi(1) and chi(2) values are underestimated with respect to experiment[2]. Indeed, these derivatives have large ground-state dipole moments and the resulting polarizing electric field should be taken into account, which has been achieved only in a few studies[3]. In this contribution, a cheap computational method is presented. It allows for the precise calculation of chi(1) and of chi(2) with the crystal structure as the only experimental input and with inclusion of the molecular dipole polarization.

From this theoretical investigation we observe that experimental chi(1) and chi(2) values can be reproduced and analyzed in terms of intermolecular interactions when i) the effects of the uniform dipole electric field are accounted, ii) the geometries of the constituting molecules are optimized with quantum-chemistry methods, and iii) the molecular electric properties are calculated by combining MP2 static response with TDDFT frequency dispersion within the multiplicative scheme.

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8828-1, Session 1

Responsive cholesteric liquid crystals *(Invited Paper)*

Timothy J. Bunning, Jonathan P. Vernon, Air Force Research Lab. (United States); Nelson V. Tabiryan, Svetlana V. Serak, BEAM Engineering for Advanced Measurements Co. (United States); Vincent P. Tondiglia, Mariacristina Rumi, Kyung Min Lee, Michael E. McConney, Timothy J. White, Air Force Research Lab. (United States)

Novel combinations of photosensitive materials and electro-optic fluids open up the coupling of stimuli-driven modulations of the optical properties of liquid crystal cells. We present here recent work on the ability to control the optical properties of electro-optic cholesteric liquid crystal cells using light. This talk will focus on the surface driven photo-modulation of aligned, bulk cholesteric liquid crystal cells.

8828-2, Session 1

Light-driven supramolecular chiral materials: photoinduced control of liquid-crystalline helical structures and non-destructive erasable molecular memory for photonic applications *(Invited Paper)*

Masuki Kawamoto, Natsuki Shiga, RIKEN (Japan); Kazuto Takaishi, Seikei Univ. (Japan); Takafumi Sassa, RIKEN (Japan); Takashi Yamashita, Tokyo Univ. of Science (Japan); Yoshihiro Ito, RIKEN (Japan)

Light-driven supramolecular chiral materials composed of an azobenzene moiety as a photoresponsive part and a binaphthyl moiety as a chiral part were designed and investigated. The materials exhibited reversible change in a dihedral angle of the binaphthyl moiety when photoisomerization of the azobenzene moiety was induced upon photoirradiation. We developed two types of optically active azobenzenes, acyclic and macrocyclic materials, as bistable chiral materials to be used for chiroptical phototriggers.

Acyclic chiral materials exhibited dynamic molecular motion induced by light and temperature. The chiral materials were dissolved in nematic (N) liquid crystals (LCs) to produce a chiral N phase with a helical structure. Helical pitch length of the chiral N LC decreased when temperature increased, because a molecular twisting motion of the binaphthyl moiety occurred in the LCs. On the other hand, length of the helical pitch increased upon photoirradiation, and then the resulting LC mixture was found to show photoswitching between chiral N and N phases upon trans-cis isomerization of the azobenzene moiety without the molecular twisting motion.

Light-driven chiral macrocycles exhibited specific suppression of cis–trans thermal back isomerization of the azobenzene moiety. The lifetime of the material at 298 K is 52.6 days, which is extremely long compared with those of azobenzene derivatives previously reported. Because of these desirable characteristics, the non-destructive molecular memory of the compounds was explored. When the chiral macrocycles were irradiated at 365 and 436 nm, the molecular twisting motion could be induced by trans–cis and cis–trans photoisomerization of the azobenzene moiety, respectively. In contrast, optical rotation was monitored by irradiation at 589 nm without any substantial changes, because the chiral compounds were inactive toward photoisomerization at this wavelength.

8828-3, Session 1

Electrically variable liquid crystal lenses for auto focus applications *(Invited Paper)*

Tigran V. Galstian, Univ. Laval (Canada)

Over the 120 years of liquid crystal research and development, we have seen at least one successful consumer electronic product incorporating those materials; the flat panel LCDs. Huge investments have been done to build corresponding manufacturing infrastructures, which is an excellent platform to help to introduce new applications. Until recently, only the polymer dispersed liquid crystal windows might benefit from these infrastructures. However, new electrically variable devices, such as switchable windows or lenses, are being actively developed now (using liquid crystals). In fact, liquid crystal lenses are already available to the public (Skype certified auto focus webcams sold by Amazon and Best Buy).

In this review talk, I will present the today's most important area of application of electrically variable lenses; the auto focus in mobile cameras. I will describe the currently available voice coil motor solutions and also the alternative approaches, such as the liquid or deformable lenses. I will then focus on various geometries used to obtain electrically variable liquid crystal lenses. I will present some of most advanced approaches in this area. I will conclude by describing some other potential applications of those lenses, including in biomedical devices.

8828-4, Session 1

Photorefractive effect in ferroelectric liquid crystals containing oligo-thiophene chiral compounds *(Invited Paper)*

Takeo Sasaki, Yumiko Naka, Tokyo Univ. of Science (Japan); Masashi Ikegami, Satoshi Kajikawa, Tokyo Univ of Science (Japan)

The photorefractive effect in photoconductive ferroelectric liquid crystals (FLCs) that contain photoconductive chiral compounds was investigated. Terthiophene and quaterthiophene compounds with chiral structure were chosen as the photoconductive chiral compounds and mixed with an achiral smectic C liquid crystal. The mixture exhibited the ferroelectric chiral smectic C phase. The photorefractivity of the mixture was investigated by two-beam coupling experiment. It was found that the FLC containing the photoconductive chiral compound exhibit a large gain coefficient of over 800 cm-1 and a fast response time of 1.4 ms.

8828-5, Session 2

Liquid crystal lasers *(Invited Paper)*

Juergen Schmidtke, Univ. Paderborn (Germany)

During the past decade, photonic band edge lasers based on cholesteric liquid crystals (CLCs) have attracted considerable interest. We give a review of various aspects of these self-assembled, tunable, coherent light sources:

The heat which is dissipated during the pumping process disturbs the cholesteric order, which is detrimental to lasing performance. We show, that stabilization of the cholesteric order -- either by crosslinking of reactive mesogens, or by application of an electric field along the helical axis of a system with negative dielectric anisotropy -- reduces the threshold and increases the slope efficiency of laser emission.

We demonstrate broad-band mechanical tuning of a LC laser based on a cholesteric elastomer, as well as high-precision fine tuning by electric-field induced distortion of the cholesteric helix.

Discontinuities in the chiral photonic structure give rise to additional resonant modes with small spatial extension and high quality factor. We prepared a phase jump in the cholesteric helix by stacking two layers of a highly crosslinked CLC polymer. The resulting photonic defect mode can be used for the generation of low-threshold laser emission (lasing threshold one order of magnitude lower than in conventional CLCs).

We demonstrate uniform alignment and narrow-band emission of a CLC between polydimethylsiloxane (PDMS) substrates. The formation of a CLC monodomain is promoted by using conventional substrates (coated with rubbed polyimide as alignment layer) as mold for casting the PDMS substrates. With PDMS being the standard material for the fabrication of microfluidic devices, this opens a simple and flexible route for system integration of LC lasers for lab-on-a-chip applications.

8828-6, Session 2

Liquid crystal chiroptical polarization rotators for the near-UV region: theory, materials, and device applications *(Invited Paper)*

Debra J. Saulnier, Brittany N. Taylor, Kelly McNabb, Kenneth L. Marshall, Terrance J. Kessler, Stephen D. Jacobs, Univ. of Rochester (United States)

The helical structure of a chiral nematic liquid crystal (CLC) material produces a number of interesting optical properties, including selective reflection and optical rotatory power. To take advantage of the high optical rotation near the selective reflection peak in the UV, either large concentrations of chiral components or those possessing very large helical twisting powers (HTP) are necessary. It is difficult to find chiral twisting agents that do not degrade UV transmission. We report what we believe to be the first experimental observation of extraordinarily high optical rotation (> 30°/?m) in the near UV for a long pitch (13.84 ?m) CLC mixture composed of the low-birefringence nematic host ZLI-1646 doped with a low concentration (e.g., 1 wt. %) of the chiral dopant CB15. This experimental finding was verified theoretically using a mathematical model developed by Belyakov, which improves on de Vries' original model. Optical rotation far from the selective reflection region is taken into account by considering the nonlinearity of the optical rotation as a function of LC layer thickness. Using this model, the optical rotation at ?=355 nm for the 1% CB15/ZLI-1646 mixture was determined computationally, with the results in good agreement with experimental data obtained by evaluating a series of wedged cells using an areal mapping, Hinds Exicor 450XT Mueller Matrix polarimeter.

This finding now opens a path to novel LC optics for numerous near UV applications. One such envisioned application for this class of materials is in UV Distributed Polarization Rotators (UV-DPR's) for high-peak-power lasers.

8828-7, Session 2

Lasing effect in blue phase liquid crystal *(Invited Paper)*

Tsung-Hsien Lin, National Sun Yat-Sen Univ. (Taiwan)

Blue phases (BPs) are highly chiral mesophases with highly fluid three-dimensional (3-D) cubic defects structures. They exist between the isotropic phase and the cholesteric phase, and can be classified as BPIII, BPII, and BPI in order of emergence attended by the decrease in temperature. Owing to their self-assembly feature, the blue phase can be regarded as a 3-D photonic crystal. This presentation show the lasing effects in blue phase liquid crystal. In the first section, we report on the relationship between the output directions of BP band-edge laser and the rubbing (alignment) directions. The 3-D periodic structure enables band-edge lasing in blue phase liquid crystals. The rubbing direction may dominate the crystal direction and thus determine the lasing directions. In the second section, we report on the switchability and the tunability of BP random laser devices, including coherence, mode stability, excitation threshold and lasing spectrum. On account of their self-assembly, polycrystalline texture appears upon cooling from the isotropic liquid. Even though the BPLCs are optically isotropic on a macro scale, discontinuous grain boundaries among platelets still cause weak light scattering. Random distributed micron-scaled platelets contribute to coherent random lasing in the BP due to the discontinuity across grain boundaries; whereas the cholesteric phase exhibits only incoherent type. Both types can be switched to each other at room temperature based on the thermal hysteresis effect. Mode-stability, the randomness of lasing wavelengths, is found to be determined by the platelet size and the addition of polymer network.

8828-8, Session 2

Tunable metamaterial in the terahertz regime using liquid crystals *(Invited Paper)*

Robert G. Lindquist, Daniele Lo Forti, Abubaker Tareki, Junpeng Guo, The Univ. of Alabama in Huntsville (United States)

Researchers at the University of Alabama in Huntsville are investigating tunable materials for phase and polarization management in the terahertz regime. Since these materials are not available in nature, artificial materials using liquid crystals for tuning need to be engineered. In this effort, the metamaterials comprise of a layers of Teflon, films of liquid crystal and patterned gold. By using a stratified structure, the LC films can be kept relatively thin and thus have a modest (0.1s) response time. However, the transmission properties of electrodes become a critical issue especially in the In the terahertz regime. We have investigated several patterned electrodes utilizing plasominc effects to optimize transmission and polarization properties.

8828-9, Session 2

Photoalignment change in pi-conjugated dye-doped LC system *(Invited Paper)*

Motoi Kinoshita, Atsushi Shishido, Tokyo Institute of Technology (Japan)

Liquid crystals (LCs) have unique properties such as self-organizing nature, cooperative motion, anisotropy in optical, electrical and magnetic properties, and alignment change by external stimuli. The key technique to use LCs for application is how to control their alignment precisely. Especially in recent years, many researchers have developed ways of controlling LC alignment by light instead of using rubbed polyimide film or electric field. In this study, photoalignment behavior of LC system containing various pi-conjugated dye was explored.

8828-10, Session 3

Surface plasmon polaritons in metal-liquid-crystal nanostructures *(Invited Paper)*

Ying Gu, Qihuang Gong, Peking Univ. (China); Iam Choon Khoo, The Pennsylvania State Univ. (United States)

Surface Plasmon polaritons (SPPs), originated from the collective oscillations of free electrons in metal, have the applications in SERS, nanosensors, nanowaveguides, solar cells, nonlinear optics and quantum optics. The existence or occurrence of SPPs is greatly relative to the dielectric permittivity of dielectric surrounding the metal. The tunability of permittivity tensor of liquid crystal (LC) can effectively modulate the properties of SPP.

By orienting the optical axis of LC, we found the large spectral tunability of narrow geometric resonances of arrays of metallic nanoparticles [1]. In Plasmon-LC wavguides, by varying its optical axis, we obtained two kinds of mode transformation: mode recombination, accompanied by dramatically extended propagation lengths at the cutoff angles, and mode alternation, associated with an obvious shift of the electromagnetic energy flux from one insulator to the other [2], as well as the quasiguided

SPPs [3]. Finally, we investigated the effects of dielectric anisotropy on SPPs in three-layer anisotropic-dielectric-metal nanostructures [4]. The numerical results indicate that the propagation length of conductor-gap-dielectric mode and its cutoff thickness changed greatly varying the optical axis. These findings may have prospective applications in actively-modulated plasmon-based nanodevices and tunable single surface plasmons sources.

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8828-11, Session 3

Liquid-crystalline self-assembling nanoparticles with dendrimeric outer corona *(Invited Paper)*

Kiyoshi Kanie, Tohoku Univ. (Japan)

Nanoparticle (NP)-based periodic structure formation has attracted a considerable attention in material science, because new synergistic functions could be derived from the periodic structure. Among organic soft materials, liquid-crystalline (LC) organic dendron is one of the most representatives to form spherical dendrimer-like structures by the self-assembling property. Such spherical assembly spontaneously forms a self-organized periodical structure. Thus, we focused our attention on introduction of such self-organization ability into inorganic NPs. As dendrons, we synthesized phenetyl ether-type dendrons G1-G3 with an amino-group at the apex. G1-G3 themselves show thermotropic LC phases. The dendrons are attached as the outer corona, through amidation, to the carboxylic groups at the surface of the inner aliphatic corona encapsulating the NP. Purpose-designed CO2H-modified monodisperse gold NPs A1-A3 were synthesized uisng 12-dodecanethiol (DT) and 16-mercaptohexadecanoic acid (MHA). The DT/MHA molar ratio was fixed to 1/1, 3/2, and 4/1 for A1, A2, and A3, respectively. SAXS measurement revealed that G2-modified A2 showed an LC hexagonal columnar phase at 130 ?C and formed a simple cubic (SC) LC phase at 150 ?C. The dendron-modified gold NPs G/A can be regarded as organic-inorganic hybrid dendrimers with thermotropic LC behaviour. The effects of dendron generation and surface coverage by dendrons on the mode of self-organization of NPs were also investigated. The technique also applied to CdS NPs.

Reference

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8828-12, Session 3

Conformation and chirality in liquid crystals *(Invited Paper)*

John L. West, Lei Zhao, Kent State Univ. (United States)

Molecular conformation plays a critical role in determining the helical twisting power, HTP, of chiral additives in a liquid crystal host. We studied the relative population of different conformers for chiral additives based on an isosorbide benzoate ester core. Molecular modeling revealed two lowest energy states with very different conformations for this core. A simple Boltzman distribution shows that substantial changes in the relative population will occur for conformers with free energy differences of 1-2 Kcal/ mole. For lower energy differences the conformers will maintain an essentially statistical distribution of the temperature range of interest while for larger differences in the free energy the lowest energy conformer will dominate at all temperatures of interest. If the conformers have very different helical twisting powers (as expected from the molecular modeling for the isosorbide cores) this will translate in to a large temperature dependence of the HTP. A clear isosbestic point in the ultra-violet absorption spectra confirms two stable conformers for one of the isosorbide benzoate esters. This is confirmed also by proton NMR. Combined with the molecular modeling, these spectra reveal how the relative populations of these two conformations change with temperature and how this is related to the helical twisting power. Temperature dependent changes in conformation can explain many of the observed anomalous responses of HPT to temperature.

8828-13, Session 3

Electrical-switched positive and negative refraction in nanosphere dispersed liquid crystal metamaerial

Grzegorz Pawlik, Wroclaw Univ. of Technology (Poland); Wiktor Walasik, Institut Fresnel (France); Karol Tarnowski, Antoni C. Mitus, Wroclaw Univ. of Technology (Poland); Iam Choon Khoo, The Pennsylvania State Univ. (United States)

We discuss the concept of reversible electrical switching between positive and negative refraction in nanosphere dispersed liquid crystal (NDLC) metamaterial for TM polarization. The proposed design offers an interesting possibilities of real-time control using external electric field of positive-negative refraction and reflection for the Poynting vector at infrared frequencies. Exemplary switching parameters and physical composition of the material are theoretically demonstrated. Finite Element (FE) simulations (Comsol) confirm this effect.

8828-14, Session 4

Defect and domain patterning in mechanically adaptive liquid crystal polymer networks

Timothy J. White, Michael E. McConney, Jeong Jae Wie, Vincent P. Tondiglia, Kyung Min Lee, Air Force Research Lab. (United States); Angel Martinez, Ivan I. Smalyukh, Univ. of Colorado at Boulder (United States)

The ability to dictate the self-organization of liquid crystalline polymer networks to form monolithic films composed of complex defect and domain patterns is reported. Using photoalignment materials and spatio-temporal control of intensity and polarization of the patterning light source – we report on the thermally and optically generated mechanical response observed in glassy, liquid crystal polymer networks. The thermally or optically generated strain within the films can yield outputs including adaptive topography or self-folding.

8828-15, Session 4

One-dimensional photonic crystals containing memory-enabling liquid-crystal defect layers *(Invited Paper)*

Po-Chang Wu, Wei Lee, National Chiao Tung Univ. (Taiwan)

Incorporating liquid crystal (LC) as a defect layer in a photonic crystal (PC) leads to the electrically tunable optical spectrum in defect modes within the photonic band gap. Such a superior feature makes the hybrid structure potential for designing various types of optical devices. Recently, we have demonstrated several types of photonic structures based on one-dimensional (1-D) PC containing memory-enabling LC (MELC) as a defect layer. The optical state remains unchanged after removal of applied voltage in the memory state. The defect modes of a PC/MELC cell can be switched to not only the voltage-sustained states but the memory or optically stable states. Owing to the fact that the spectral properties of defect modes in a memory state persist without applied voltage, the device will support the green society of tomorrow.

The wavelength tunability, amplitude tunability and optical multistability of the defect modes permit the 1-D PC/MELC cell to be alluring for photonic device applications such as low-power-consumption multichannel filters, light shutters or electrically controllable intensity modulators without any polarizers.

In this invited talk, our recent development of various one-dimensional PC/LC hybrid cells for photonic applications will be presented. Special attention will be paid to the optical and spectral properties of multilayer PC structures containing a bistable chiral-tilted homeotropic nematic (BHN) layer, a bistable chiral-splay nematic (BCSN), a bistable dual-frequency cholesteric LC (DF-CLC) layer, a tristable polymer-stabilized cholesteric texture (PSCT), and a tristable smectic-A liquid crystal as a defect layer.

8828-16, Session 4

Electro-optic and spectroscopic studies of liquid crystals functionalised with ferroelectric nanoparticles *(Invited Paper)*

Malgosia Kaczmarek, Nina Podoliak, Oleksandr Buchnev, Mark Herrington, Univ. of Southampton (United Kingdom); Jean-Francois Blach, Jean-François Henninot, Marc Warenghem, Univ. Lille Nord de France (France)

Ferroelectric nanoparticles, dispersed in nematic liquid crystals, can lead to significant changes in the host's physical properties, namely birefringence, dielectric anisotropy and clearing temperature. Such functional liquid crystals are complex systems, where the dynamics is governed by different relaxation processes, including liquid crystal switching, the nanoparticle reorientation, and the liquid crystalline relaxation around nanoparticles. Our recent work demonstrated the impact of nanoparticles on some fundamental parameters, such as elastic constants, viscosity and response time.

We report on the results obtained with two different types of ferroelectric nanoparticles, BaTiO3 and Sn2P2S6, dispersed in a low birefringence liquid crystal LC18523 and in low ionic content and high birefringence liquid crystal TL205 (Merck). The electro-optic study showed that ferroelectric nanoparticles cause a significant increase of the dielectric anisotropy and also reduce the splay elastic constants. Both of these effects lead to a decrease in the threshold voltage up to a factor of 1.8. Liquid crystal switching behaviour in twisted cells was also used to estimate dynamic parameters, such as rotational viscosity for the suspensions, indicating its increase by a factor of up to 3.2.

Furthermore, the interaction between the organic and inorganic elements of the functionalised liquid crystals colloids was investigated using spectroscopic ellipsometry and Raman scattering. New, intense bands of the Raman signal were detected for the liquid crystals functionalised with two different types of ferroelectric nanoparticles, indicating strong interaction between the liquid crystal molecules and the nanoparticles.

8828-17, Session 4

A biosensor of high-density lipoprotein of human serum on a liquid crystal and polymer composite film *(Invited Paper)*

Yi-Hsin Lin, Kai-Han Chang, Wei-Lin Chu, Yu-Shih Tsou, National Chiao Tung Univ. (Taiwan); Li-Ching Wu, Chien-Feng Li, Chi Mei Medical Ctr. (Taiwan)

High-density lipoprotein (HDL) is one of the major carriers of cholesterols in the human blood. The high level of HDL in human body has beneficial effects to cardiovascular diseases and reducing the risk of Alzheimer's disease. Recently, we have developed a switchable surface, liquid crystal and polymer composite film (LCPCF), and also developed many applications based on LCPCF, such as lenses, electro-optical switches, and sperm testing devices. In this paper, a biosensor for the concentration of high-density lipoprotein in human serum on the LCPCF is demonstrated. The sensing mechanism is based on a polar-polar interaction between orientation of LC directors and HDL in human serum. From the experiments, the concentration of HDL in human serum with a change of polarity affects the orientations of LC directors at the interface between LCPCF and human serum. In addition, the surface free energy of LCPCF can be changed with the applied voltage due to the electrically tunable orientations of LC directors anchored among the polymer grains of LCPCF. As a result, the droplet motion of human serum on LCPCF under applied voltages can sense the concentration of HDL in human serum even though the surface tension of human serum remains the same with the concentration of HDL. The impact of this study is to design an inexpensive, fast, and portable biosensor for sensing the diseases related to high-density lipoprotein in human blood.

8828-18, Session 4

Nanosecond electro-optic switching of a liquid crystal

Volodymyr Borshch, Sergij V. Shiyanovskii, Oleg D. Lavrentovich, Kent State Univ. (United States)

Electrically induced changes in optical properties of liquid crystals (LCs) represent a broad platform for modern technologies. The most widely used is the Frederiks effect, i.e. collective reorientation of molecules caused by dielectric anisotropy of the LC. Its Achilles' heel is a slow (millisecond) relaxation from the field "on" to the field "off" state. We present an electrooptic effect in a LC with the response time shorter than 100 ns to both the field on and field off driving. The effect is caused by electric field induced modification of the order parameter (EMOP) and does not require molecular reorientation.

To demonstrate the concept of EMOP, we use a nematic LC with negative dielectric anisotropy. The electric field is perpendicular to the director. Although the field does not reorient the molecules, it causes two other effects. First, it changes the components of dielectric tensor at optical frequencies (optic tensor). Second, it modifies the director fluctuations. The two effects have very different response times, nanoseconds for EMOP and milliseconds for director fluctuations. The principal difficulty is to eliminate the slow contribution of director fluctuations to the optical response. We achieve it by using a special oblique scheme of light propagation. As a result, the nematic cell shows a fast response, around 30 ns, to both the field on and field off driving. By separating the uniaxial and biaxial contributions to EMOP we show that the relaxation time of the latter is around 1 ns. The work was supported by DOE grant DEFG02-06ER46331.

8828-19, Session 5

Liquid crystal tunable optical vortices *(Invited Paper)*

Yan-Qing Lu, Wei Hu, Nanjing Univ. (China)

We present a technique for producing tunable optical vortices by using liquid crystal (LC) fork gratings. To write gratings in to LC cells, a home-made micro-lithography system with a digital micro-mirror device (DMD) as dynamic mask forms arbitrary micro-images on photoalignment layers and further guides the LC molecule orientations. The current resolution of 5 ?m is realized, while it is still improvable. Arbitrary fine photo-patterning fork gratings with various pitch sizes, prongs and LC alignments are thus obtained. The diffraction properties for both infrared and visible lights are studied. Clear optical vortices with designed topological charges are obtained showings in different diffraction orders. When a voltage is applied on the cell, index re-distribution is induced due to the realignment of LC molecules, and then the optical vortices become tunable. Dynamic switching between Gaussian modes and vortex beams are thus achieved. These advantages make the device appealing for single-molecule optical tweezers, orbital angular momentum multiplexing in optical communications and even future quantum computing.

8828-20, Session 5

Low-voltage tunable photonics devices: grove on thin porous structures containing liquid crystals *(Invited Paper)*

Luigino Criante, Istituto Italiano di Tecnologia (Italy) and Univ. Politecnica delle Marche (Italy); Francesco Scotognella, Politecnico di Milano (Italy)

Future key technologies in the field of electronic switches and processes replacement by all optical devices have to mix the achievement of very high density integrated optic devices with a significant electro-optic tuning capability. To reach these technological challenges high operation speed, power dissipation and low voltage circuit design are the problems out for solution. The porous materials infiltrated with liquid crystal give a great potential for tunable photonic devices due to their tunable physicochemical properties. It shows both practical and fundamental interest and it may open the way to satisfy all new technology requirements.

In this study we present the fabrication and the optical characterization of a very thin but efficient photonic crystal made by metal oxide nanoparticles, infiltrated with the nematic liquid crystal (E7) by drop casting in a simple and fast procedure. The real time analysis of the photonic band-gap during the infiltration shows a red shift (60 nm) due to the increase of an effective refractive index of the multilayer. The effect of an applied electric field has been studied and we report a blue shift of 8 nm with only 8 Vrms, corresponding approximately to an electric field of 3.4 V/µm, one order of magnitude smaller with respect to previously reported tunable liquid crystal infiltrated photonic crystals. The performances obtained - improvement through the choice of the most suitable liquid crystals for lower voltage operation - could be very interesting for realization of low cost and portable switching devices for high density integrated optics.

8828-21, Session 5

Large color tuning of polymer stabilized negative dielectric anisotropy cholesteric liquid crystals

Kyung Min Lee, Air Force Research Lab. (United States) and Azimuth Corp. (United States); Vincent P. Tondiglia, Lalgudi V. Natarajan, Air Force Research Lab. (United States) and SAIC (United States); Michael E. McConney, Air Force Research Lab. (United States) and Azimuth Corp. (United States); Timothy J. Bunning, Timothy J. White, Air Force Research Lab. (United States)

We report on the electro-optical responses of polymer stabilized CLCs upon application of DC fields by varying chiral dopants. Red-tuning of the cholesteric notch (~400nm at 70V DC) was observed in cells containing chiral LC monomer (SL04151) or achiral LC monomer (RM257) with chiral dopants R1011 and R811 combined with negative dielectric nematic LC ZLI-2079. Interestingly, broadening or tuning of the notch was seen when a combination of R1011 and R811 chiral dopants was used with achiral monomer RM257. Surprisingly, only notch tuning was observed when the chiral LC diacrylate monomer (SL04151) was used for the polymer stabilization. The mechanism involving ion transport leading to the deformation of the template polymer network as the precursor leading to the tuning or broadening will be discussed.

8828-22, Session 5

Liquid crystal near-IR laser beam shapers employing photoaddressable alignment layers for high-peak-power applications *(Invited Paper)*

Kenneth L. Marshall, Debra J. Saulnier, Univ. of Rochester (United States); Haiqing Xianyu, Svetlana V. Serak, Nelson V. Tabiryan, BEAM Engineering for Advanced Measurements Co. (United States); Christophe Dorrer, Univ. of Rochester (United States)

Spatial beam shaping is used in high-peak-power laser systems for improved efficiency and performance. The low near-IR laser-damage threshold (230 mJ/cm2 at 1054 nm, 2.4 ns, 5 Hz) of the commercial liquid crystal-on-silicon (LCOS) programmable spatial light intensity modulators (PSLIM's) currently used on OMEGA EP limits their use to the low-fluence areas located in the front end of the long-pulse beamlines. Other limitations of these devices include both a relatively small device clear aperture (12 mm ? 16 mm) and low-pixel density (600 ? 792). In previous work, we demonstrated that passive near-IR LC beam shapers with laser damage thresholds ≥30 J/cm2 at 1054 nm (both 1-on-1 and N-on-1 testing at 1 ns) are achievable using coumarin alignment layers patterned by contact photolithography. We report on efforts to apply this technology to near-IR LC beam shapers to make them capable of being switched optically between two different patterned alignment states. Such reversible switching is accomplished using low-energy polarized UV and visible light incident on a "command surface" containing photoswitchable azobenzenes or spiropyrans, with pattern writing conducted using polarized UV photolithography or by raster scanning with a pulsed UV laser. Pattern erasure is achieved using either visible light or UV light with a different polarization orientation than used to write the pattern. The ability to reversibly write and erase patterned optical states "on-demand" in an assembled device combines the high resolution and high laser-damage resistance of current passive photopatterned LC beam shapers with the flexibility and in-system write/erase capability of the PSLIM device without requiring conductive coatings that compromise the laser-damage threshold.

8828-23, Session 5

The science (and art) of switching diffractive waveplates *(Invited Paper)*

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Diffractive waveplates present modulation of optical axis orientation at high spatial frequencies induced and supported by conditions at the boundaries. Their electro-optical and all-optical tuning and switching characteristics are as complex as in cholesteric liquid crystals where the modulation is supported by intermolecular forces. We will discuss the specifics and will outline the conditions for tuning and switching different varieties of diffractive waveplates avoiding long transients and hysteresis typical to liquid crystalline materials with complex orientation state.

8828-24, Session 6

Novel siloxane based smectic A liquid crystal materials: formulation, structures, and optical device applications *(Invited Paper)*

D. P. Chu, W. A. Crossland, A. B. Davey, Mykhaylo N. Pivnenko, Huan Xu, Andriy Dyadyusha, John R. Moore, Univ. of Cambridge (United Kingdom); Terry V. Clapp, Dow Corning Ltd. (United Kingdom); Jonathan P. Hannington, Dow Corning Corp. (United States)

An overview of the recent development of novel siloxane based smetic A liquid crystal materials developed for optical device applications. Flexibility in formulation, robust and stable smetic A phases, excellent uniformity and extremely long lifetime will be presented.

8828-25, Session 6

3D microscope system by using a liquid crystal lens and an LED ring illumination

Marenori Kawamura, Shunsuke Ishikuro, Akita Univ. (Japan)

When microscopic three-dimensional (3D) objects are observed by using a conventional microscope, the focused and defocused images can be obtained in same area. It is remarkable that the effect of focused and defocused images depends on the magnification of the objective lens (numerical aperture; NA) since a depth of field is inversely proportional to the NA of the lens. When the positions of the camera or the object is moved in the depth direction, the variation of the image magnification with focus occurs.

In our group, many types of optical devices using nematic liquid crystal (LC) materials with a large birefringence and dielectric anisotropy have been developed. Prof. Susumu Sato proposed an optical device such as an LC lens with a circularly hole-patterned electrode for tuning a focal length without any mechanical movements.

In this study, we propose a three-dimensional (3D) microscope system for tuning a focal plane in a depth direction by using a an LC lens and a light emitting diode (LED) ring illumination without any mechanical movements. The focal length of the microscope imaging system is controlled by applying the voltage to electrodes of the LC lens with double circularly hole-patterned electrodes and external flat transparent electrode. The objects can be selectively illuminated by using a light emitting diode (LED) ring illumination with controllable switching each LED. The continuous microscopic images are taken by changing the position of the focal plane. The all-focused images and depth mapping properties of the microscopic objects are obtained by processing our proposed image digital filter from contentious focal images.

8828-26, Session 6

Viewing angle compensation of various LCD modes by using a liquid crystalline polymer film *(Invited Paper)*

Takuya Matsumoto, Suzushi Nishimura, JX Nippon Oil & Energy Corp. (Japan)

We have developed liquid crystalline retardation films to improve quality of images of LCDs such as their viewing angle performance and coloration. We could achieve to make many types of optical retardation film by using rod-like liquid crystalline polymer. The resulting liquid crystalline polymer film has several advantages over conventional uni- or biaxial stretched retardation film. Optical well-controlled structures such as twisted nematic, homogeneous nematic, hybrid nematic and homeotropic structures could be stabilized for ideal compensation of various LCD modes such as STN, TN, ECB, VA and IPS modes.

Twisted nematic film is effective to cancel coloration of STN mode that is a fatal drawback for color representation.

Short pitch cholesteric film of rod-like liquid crystalline polymer, is equivalent to Negative-C plate, that can expand the viewing angle of VA LCDs.

Hybrid nematic film is quite unique film because the film works not only as a wave plate but also as a viewing angle compensator for TN and ECB modes.

Homeotropic film, positive-C plate, allows In-Plane-Switching (IPS) and Circularly-Polarized Vertical-Alignment (CPVA) LCDs to have excellent viewing angle performance. And our homeotropically aligned liquid crystalline film called “NV film” is the thinnest retardation film. The thickness of the liquid crystalline layer is a mere 1 micrometer.

Homeotropic film is useful to expand the viewing angle of not only LCDs but also OLED Displays. NV film can expand the viewing angles of the circular polarizer for antireflection of OLED Displays, in combination with a quarter wavelength plate.

8828-27, Session 6

Microseconds-nanoseconds-femtoseconds all-optical switching with liquid crystals

Shuo Zhao, Kuan Lun Hong, Iam Choon Khoo, The Pennsylvania State Univ. (United States)

We present the results of recent studies on mechanisms suitable for microseconds through nanoseconds to femtoseconds all-optical switching in liquid crystals, and compare the performance with other materials. In particular, we show that their microsecond-nanoseconds responses are ideal for nonlinear transmission and optical limiting action in temporal regimes where other nonlinear absorbers do not function.

8828-28, Session 6

Tunable photonic devices based on liquid crystals and composites *(Invited Paper)*

Rita Asquini, Antonio D’Alessandro, Univ. degli Studi di Roma La Sapienza (Italy)

Tunable photonic switches and filters employing liquid crystals (LC) and LC-composites can be used in several application fields as optical communications, sensors and imaging systems. Their excellent electro-optic, thermo-optic and nonlinear optical responses can be exploited for realizing components in guided-wave microstructures operating at low optical and electric powers.

In this review we discuss various integrated optics structures proposed and/or experimentally demonstrated for optical processing, including routers, Bragg filters and all-optical switches.

A compact (160 um long) two-way router in a nematic liquid crystal (NLC) waveguide was designed and demonstrated in the near infrared with voltage modulation as low as 0.21 V.

Wavelength-tunable voltage-controlled Bragg reflectors were analyzed in different geometries: one has a reflectivity above 80% in a 14 nm range (1530-1550 nm) with bias voltages from 2.5 to 3.0 V; another exploits coplanar comb electrodes to achieve an extended tuning range of about 104 nm (1521-1625 nm) with reflection above 50% for voltages from 2.9 to 10.2 V.

Tunable gratings realized with microstripes of polymers and NLC on glass waveguides were also characterized in the 1.55 ?m spectral window, demonstrating electro-optic filters adjustable over 4 nm for bias fields of about 3 V/?m. An all-optically tuned filter was also demonstrated in dye-doped NLC with tunability over 6.6 nm when illuminating at optical power densities not exceeding 1.43 W/cm2.

8828-29, Session 6

Phototropic liquid crystals comprising one component

Anna M. Sobolewska, Joanna Zawada, Stanislaw J. Bartkiewicz, Wroclaw Univ. of Technology (Poland); Zbigniew Galewski, Univ. of Wroclaw (Poland)

Liquid crystals (LC) are materials which due to their unique properties are widely used in everyday life. Traditional LCs are classified as thermotropic (TLC), which means that the temperature generates the mesophase, or lyotropic (LLC), in which mainly the concentration affects the phase transition. In the last few years research is being conducted on a new class of LCs in which the phase transition is induced by the light. Such materials are called phototropic liquid crystals (PtLC) and they open a new way for applications of liquid-crystalline materials in photonic devices fully controlled by the light. However, most of PtLCs have been realized by the doping a classical LC with a photochromic dye. The photochemical reaction of the photochromic molecule dispersed in a LC matrix induces changes in the alignment of the liquid-crystalline host which can lead to the phase transition, called as a photochemical phase transition.

Here we report a novel approach in which the liquid-crystalline and photochromic properties are accomplished in a single-component azobenzene-based liquid crystal. Using the phenomenon of the light control phase transition we demonstrate its application in optical memories. We were able to realize optical ROM and RAM types of memories using one material.

Acknowledgements

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8828-30, Session 7

Defect structures in liquid crystals bounded by microwrinkles *(Invited Paper)*

Takuya Ohzono, Jun-ichi Fukuda, Yoshiko Takenaka, National Institute of Advanced Industrial Science and Technology (Japan)

Spatially confined liquid crystals (LCs) exhibit non-uniform alignment, often accompanied by self-organized topological defects of non-trivial shape in response to imposed boundary conditions and geometry. Here we show that a nematic LC, when confined in a sinusoidal microwrinkle groove, exhibits a new periodic arrangement of twist deformations and a zigzag line defect [1]. This periodic ordering results from the inherent LC elastic anisotropy and the antagonistic boundary conditions at the flat LC-air and the curved LC-groove interfaces. The periodic structure can be tuned by controlling the groove geometry, which demonstrates the importance of boundary conditions and introduced asymmetry for the engineering of topological defects. The temperature dependence of the structure also shows nontrivial transformation of the defects [2]. Moreover, the kinks in the zigzag defects can trap small particles, which may afford a new method for manipulation of colloids. Our system, which uses easily fabricated microwrinkle grooves, provides a new microfabrication method based on the arrangement of controllable defects, which can be applied for other LC phases [3].

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8828-31, Session 7

Topological reorientation of liquid crystals with optical vortices *(Invited Paper)*

Mohamed El Ketara, Charles Loussert, Etienne Brasselet, Univ. Bordeaux 1 (France)

The optical reorientation of liquid crystals is a research topic for a long time since the discovery of the optical Fréedericksz threshold in the early eighties. A few years ago, the concept of topological optical reorientation has been introduced, namely the writing of orientational patterns endowed with topological features. Surprisingly, this can be achieved by using "regular" Gaussian beams whereas the seemingly more obvious case of "singular" beams, optical vortices, also works. In this presentation, a review of the results obtained so far will be given and our latest results regarding topological patterning induced by optical vortices will be presented.

8828-32, Session 7

Properties of the self-deforming Nx phase in mesogenic dimers *(Invited Paper)*

Vitaly P. Panov, Jagdish K. Vij, Reshma Balachandran, Trinity College Dublin (Ireland); Volodymyr Borshch, Oleg D. Lavrentovich, Kent State Univ. (United States); Maria-Gabriela Tamba, Georg H. Mehl, The Univ. of Hull (United Kingdom)

An overview of the most recent experiments performed to reveal the structure of the Nx phase will be given. This new phase provides typical for nematics X-ray diffraction pattern and is found at temperatures below the conventional nematic phase in odd-chain hydrocarbon linked mesogenic dimers.

The materials in the Nx phase form self-deformed striped pattern parallel to the rubbing direction in planarly aligned rubbed cells with a well-defined period. The period is found to depend on the cell spacing. The self-deformation stripes appear without any external electromagnetic field or thickness gradient across the cell.

Although the materials are composed of non-chiral molecules, the low temperature nematic phase exhibits fast linear optical response of the order of a few microseconds. This response is reminiscent of the phase exhibiting chirality.

Moreover, at high fields some of the materials form striped domains with opposite direction of the optical response. These are normal to the rubbing direction and their periodicity exhibit voltage and frequency dependence.

The Freedericksz transition in this phase also shows unusual properties and has proven to be of the first order.

The experiments to be presented include polarized microscopy observation, birefringence mapping and optical contrast spectroscopy. Possible causes of the phenomena will be discussed.

8828-33, Session 7

Tuning SmAPf mesogen structure for different applications

Eva D. Korblova, David M. Walba, Jan Porada, Maria Kolber, Joseph E. Maclennan, Matthew A. Glaser, Renfan Shao, Yongqiang Shen, Cheol S. Park, Noel A. Clark, Univ. of Colorado at Boulder (United States)

We recently described the first SmAPf mesogen W586, which exhibits analog electrostatic V-shaped switching and analog phase modulation in LC cells. This was followed with directed design and synthesis of a very high polarization SmAPf mesogen exhibiting V-shaped switching with optical latching. Here we report the design, synthesis, and characterization of new SmAPf mesogens, with the goal of controlling properties important in various applications, including phase modulation depth, ferroelectric polarization, and electronic second order nonlinear optics (NLO).

In order to increase the maximum phase modulation depth (change in birefringence $\partial(\Delta n)$ achievable in V-shaped switching, mesogens possessing a diphenylthioether in the center of the bent core were prepared. It was expected that this structure would decrease the "bite angle" between the two "wings" of the core compared to the known m-disubstituted aromatic rings, and that this would increase the ∂(Δn) achievable in V-shaped switching. Other SmAPF mesogens were designed to adjust spontaneous polarization in the SmAPf phase. It was anticipated that this could be achieved by changing the orientation of phenylbenzoate ester linking groups along the core. Other work involving design of mesogens for electronic second order nonlinear optics has also been undertaken.

The characterization and EO properties of the new materials of will be discussed. Results suggest the SmAPf phase constellation shows great promise for application in fast phase-only EO modulators.

8828-34, Session 8

New LC materials with small absorption for photonic devices in THz range *(Invited Paper)*

Janusz R. Parka, Military Univ. of Technology (Poland)

During last few years many interesting applications of liquid crystal materials in THz range are expected. The properties of different liquid crystal materials are widely investigated in this range.

From application point of view the most important of liquid crystal materials is obtaining the low tangent of losses in wide frequency range with relatively high coefficient of tunability. These properties can be changed and adjusted to dedicated applications. Our last investigations shown that is possible to modified the structure of LC molecules to reduce the tangent of losses to value about 10-3 with tunability about 40%. New LC materials consisted of fluorinated atoms with low loss tangent and high transparency in 0.3 – 3 THz were spectrally characterized and used in tunable phase shifter and phase grating. Fluorinated liquid crystal compounds have low absorption in the THz band in comparison with commercially available LCs like 5CB. The properties of these device have been described.

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8828-35, Session 8

Effects of UV curable liquid crystals on electro-optical properties of polymer stabilized liquid crystal displays (PS-LCDs) *(Invited Paper)*

Toru Fujisawa, DIC Corp. (Japan)

It is a recent attractive approach to use polymer/liquid crystal composite for the breakthrough of the performance of a LCD. The applications of UV-curable liquid crystals such as the light scattering LCD using polymer network liquid crystals (PNLC) and polymer stabilized V-shaped ferroelectric LCD (PSV-FLCD) are reviewed, and the effects of UV curable liquid crystals on electro-optical properties of PSV-FLCD are discussed. The cross linked liquid crystalline polymer formed from a small quantity of UV curable liquid crystals plays an important role to exhibit several interesting properties such as a fast relaxation time with the increase of molecular interaction between the liquid crystal molecules and the polymer network. Moreover, the switching mechanism of FLCs is altered with a unique process combining a UV irradiation and an applying AC voltage. A biaxial alignment of FLCs is changed into a uniaxial alignment resulting in V-shaped switching in FLCDs and the drastic improvement on relaxation time from 500 micro seconds to 25 micro seconds is observed. By the increase of applying voltage in situ-polymerization, a uniaxial alignment is attained even in a 5 micro meters of thicker cell being independent from surface stabilization.

8828-36, Session 8

All-optical recording of liquid crystal microlenses based on light induced anchoring modification in conventional dye-doped nematic cells *(Invited Paper)*

Liana Lucchetti, Univ. Politecnica delle Marche (Italy)

We describe a simple method to obtain tunable microlenses in cells with pixel-free electrodes filled with the nematic LC 5CB doped with methyl red. The lens-like refractive index distribution is generated by the joint action of a laser beam with Gaussian intensity distribution and an external dc voltage (V) lower than the Freedericks threshold.

Lenses are obtained in conventional planar cells with not patterned electrodes. A linearly polarised pump beam from a cw He-Cd laser is focused on the sample surface. The beam waist on the sample is 100 ?m. A dc voltage below the electric Freedericksz threshold is applied perpendicular to the cell substrates.

The presence of microlens in the irradiated region is highlighted by the appearance of the Self-Phase-Modulation (SPM) rings in the far field. The ring pattern appears when the optical and the electric fields are simultaneously present. The SPM pattern is also visualised by means of a low power probe He-Ne beam, polarised parallel to the pump and microlens formation is demonstrated by the observation and modulation of the red ring pattern when the pump beam is switched off. Microlenses are electrically tunable requiring a very small variation of V, can be erased by an external bias exceeding the electric Freedericks threshold and can be renewed by lowering again the external voltage.

Experimental results are well fitted by a model based on the light-induced decrease of the LC surface anchoring energy.

8828-37, Session 8

In-situ hologram correction in SLM setup *(Invited Paper)*

Vincent Carrat, Univ. of Virginia (United States); Bruno Viaris de Lesegno, Laurence Pruvost, Lab. Aimé Cotton (France)

Liquid crystal modulators suffer from defects that need to be compensated for demanding phase modulation applications like cold atoms manipulations. By adding another wavelength in an existing SLM phase modulation setup, we developed a robust method to get the birefringence map of the modulator. In this way we are able to see and correct the defects in-situ without disturbing the running experiment.

The phase modulation is applied to a red laser beam and we monitor the birefringence map with an infrared beam. The monitoring beam is initially linearly polarized with a 45° angle between the polarization plane and the neutral axis. The outgoing polarization is elliptical and we analyze it with an polarizer and a CCD camera to measure the birefringence map. After a comparison between the measured and desired birefringence map, the defects are corrected by modifying the addressing hologram. Furthermore, the correction is done in one step, and the response time of the procedure is limited by the frame rate of the camera. For these reasons we can control time-dependent defects like those introduced by a powerful read-out beam or thermal drifting.

This method allows us to measure and correct the defects of the SLM with spatial and phase resolutions comparable to the interferometric methods. As the method relies on polarization, vibration isolations and alignments are not critical which supplies robustness. Furthermore, this method provides an in-situ measurement, which simplifies the correction required for day to day defects or aging. Finally the demonstrated method provides feasibility to a closed-loop phase correction.

8828-38, Session PWed

Active electrical and optical tuning of silicon photonic devices

Joanna N. Ptasinski, Univ. of California, San Diego (United States) and Space and Naval Warfare Systems Pacific (United States); Sung W. Kim, Lin Pang, Univ. of California, San Diego (United States); Iam Choon Khoo, The Pennsylvania State Univ. (United States); Yeshaiahu Fainman, Univ. of California, San Diego (United States)

Silicon photonics is a rapidly evolving field allowing for optical devices to be made cost effectively using standard semiconductor fabrication techniques and integrated with microelectronic chips. Active tuning of silicon photonic devices has been demonstrated using thermal, electrical and optical means in the form of injection of free carriers through two-photon absorption. This work explores active electrical and optical tuning of silicon photonic devices using silicon strip waveguides combined with nematic liquid crystal (NLC) claddings. Simulation studies are presented.

8828-39, Session PWed

Design and simulation of optical sensor based on 2D photonic crystal

Indumathi T. S., Visvesvaraya Technological Univ. (India)

Here case study for different fluids is done since the different fluid has different density and there will be variation in the dielectric constant which results in shift in the frequency from the standard value.

We analyze band structure of the immersed liquid crystal and see the waveguide existence in the band structure. This is compared with our already existing prototype. If in case the shift was matching with the existing prototype, then we see the corresponding density of the liquid. Since each liquid has its own density we can easily find which was the fluid given to us.

In Figure, we see all the waveguide modes for the given liquid The shift in waveguide was downward because the dielectric constant was increasing from our standard structure. The gap between kerosene and heptanes was very small. This is because the dielectric constant was very close to each other. But the distinct feature between them could be clearly identified upto four decimals. It is 0.2491 for kerosene, 0.2404 for heptane. So we can see that our device is sensitive even for the smallest variation in dielectric constant.

Here it is reported that the numerical and simulation study indicates proposed structure is appreciably sensitive to the refractive index of the liquid. Normally the defect will be a disadvantageous but here the defect is a boon. By creating a defect such as point defect or line defect in photonic crystal it provides number of applications such as pressure sensor, biochemical sensing etc.

8828-40, Session PWed

Influence of small particles on electrooptic effects in liquid crystals

Tahir D. Ibragimov, Gazanfar M. Bayramov, Institute of Physics (Azerbaijan)

It is known that optical properties of small particles depend on surrounding medium. In this work such medium is liquid crystal (LC) whose dielectric and optic properties along light propagation can be operated by application of electric field. We considered following problems:

- Christiansen effect in the small particles-liquid crystal system. It was shown possibility of tunable selective filtration and modulation of infrared radiation as at the electric field application with invariable frequency, and changing frequency at invariable voltage (an use of dual-frequency LC).

- Influence of conducting and dielectric particles on electrohydrodynamic instability (EHDI) in nematic LC. It was shown that the occur¬rence of silver particles in LC reduces the threshold voltage of the EHDI formation in a static field, and then it is more at low frequencies and less at high ones than in the pure LC. Meanwhile, the limiting frequency of the EHDI disappearance increases. While aluminum oxide particles reduce the threshold voltage of the EHDI occurrence at low frequencies on greater value than silver particles and they increase it at the high frequencies. A presence of particles changes rise and decay times in comparison with the pure LC. It is connected with an increase in viscosity and a reduction of elastic properties of LC and also overcoming the additional obstacles (particles) by ions.

- Influence of particles of centrosymmetric and noncentrosymmetric materials on Clark-Lagerwall effect in ferroelectric LC. It has been shown that time characteristics of a cell with LC-Al2O3 are a little bit worsened in comparison with a cell with pure LC. It is caused by increase of the rotational viscos¬ity of the ferroelectric LC with addition of small particles Al2O3. Time characteristics of the Clark–Lagerwall effect in the LC-SrTiO3 cell essentially surpass time characteristics of the cell with pure LC because the transition from the deformed UP-state to the DOWN-state demands overcoming much lower energy than the transition from the pure UP-condition to the DOWN-state.

8828-41, Session PWed

High efficient polymer dispersed liquid crystal for ultra-bright projected image

Shun-Ling Hou, National Taiwan Univ. (Taiwan)

Head-up display (HUD) commonly uses liquid crystal to generate images. However, the intensity of the light decreases a lot because of passing through the polarizers. Therefore, polarizer-free display is a way to enhance the light efficiency. We demonstrate the feasibility of using Polymer Dispersed Liquid Crystal (PDLC), which consists of polymer and liquid crystal, as an optical switch to fabricate a simple see-through projected display device. Due to the unique E-O characteristics of PDLC, it can be a role to define the projected image shape. In our device, we use the ultra-bright collimated LED as a backlight source so that the projected image can also be seen clearly in broad daylight. Besides, PDLC do not need to utilize polarizers. It is achieved to obtain very high light efficiency (~70%). In this paper, we show some results of projected images with various colors (RGB) that can be applied to see-through projected display. From our experiment result, the see-through projected display device by PDLC can achieve high contrast ratio (~1000:1) and response time is about 15~20 ms. The driving voltage is around 20~25 V. Further improvement can be achieved by optimizing the LC material/monomer concentration or others parameters.

8828-42, Session PWed

Effect of in-plane electric fields on the optical properties of cholesteric liquid crystals

Mariacristina Rumi, Vincent P. Tondiglia, Lalgudi V. Natarajan, Timothy J. White, Timothy J. Bunning, Air Force Research Lab. (United States)

A considerable body of knowledge has been developed on the general behavior of cholesteric liquid crystal (CLC) materials in electric fields,

but not all aspects have been fully explored and many of the device configurations have limitations in spectral bandwidth, tunability, response time, or dynamic range. One approach that has been reported to achieve tunability in optical filters based on CLCs with a positive dielectric anisotropy and in the planar homogeneous state involves the application of electric fields perpendicular to the axis of the CLC helix. The field leads to a progressive unwinding of the helix and a corresponding red-shift in the position of the reflection band of the CLC. We will discuss how intrinsic properties of partially unwound helices and extrinsic factors related to cell parameters and the vicinity of regions with different liquid crystal textures manifest in a decrease in reflectance and in band broadening with increase in the field strength for the Bragg reflection of this type of devices.

8828-43, Session PWed

Nonlinear optics with blue-phase liquid crystals

Iam Choon Khoo, Kuan Lun Hong, Shuo Zhao, The Pennsylvania State Univ. (United States)

Blue-phase liquid crystals with their 3-D photonic crystal structure and optical anisotropy allow polarization-free nonlinear optical switching. The freedom from surface alignment requirements also facilitate/enable integration in complex nano-structures/geometries to devise tunable metamaterials and nano-structured optical waveguides and ring-resonators. Recent experimental feasibility demonstrations of exemplary structures will be presented.

8828-44, Session PWed

Liquid-crystal micro-lens array with variable focusing and deflecting functions

Marenori Kawamura, Jyunki Teragaki, Akita Univ. (Japan); Susumu Sato, Akita Research Institute of Advanced Technology (Japan)

Liquid crystal (LC) devices with a single circularly hole-patterned electrode at the diameter of millimeter and/or micro size have been proposed by Prof. Susumu Sato. The LC device such as an LC lens with a radially-varying refractive gradient-index distribution can be realized by the LC molecular reorientation caused by an axially symmetrical electric field in the circularly hole-patterned electrode. The wave-front passing through the hole-patterned aperture of the LC lens possesses a quadratic function property. The LC lens has a very wide variable range of the focal length from the negative to positive lens properties and preserves its optical quality over the entire focus range by applying the voltages. Both a beam steering and anamorphic lens property in addition to the variable focusing function can also be controlled when the circularly hole-patterned electrode is divided into several parts and the applied voltages to the each electrode are different values.

In this study, we propose an LC micro-lens array with two-divided and hexagonal hole-patterned electrodes for varying a focal length and a beam deflection angle. The distribution of the refractive index in the hexagonal region of the LC microlens-array can be controlled by applying the voltage to the electrodes. The optical properties such as the focal length and beam deflection can be estimated by the induced refractive index distributions.

8828-45, Session PWed

Electro-optical properties of nematic liquid crystal cells in the infrared wavelength region

Marenori Kawamura, Akita Univ. (Japan); Susumu Sato, Akita Research Institute of Advanced Technology (Japan)

Liquid crystals (LCs) have optical and electrical properties such as a large tunable birefringence and dielectric anisotropy. The LCs have been extensively used in display devices and some optical tunable applications mainly in the visible wavelength region. The optical properties of LCs in the infrared region can also be changed by applying an electric field. Then, new optical devices working in the infrared region can be produced by using the LC materials. In this study, we fabricate nematic LC cells such as a homogenous and twisted nematic LC cells by using silicon wafer substrates, and evaluate their electro-optical properties at the infrared wavelength from 8 to 14 microns. The birefringence of the LC materials at this wavelength can be estimated by applying the voltage to the homogenous LC cell under crossed polarizers where the LC director is set to be 45 degrees to the polarization direction, and its value is slightly smaller than that in the visible region. The transmission light intensity through the TN LC cell is measured under crossed and parallel polarizers as a function of the voltage to the LC cell. The twisted nematic effect in the infrared region can also be obtained as well as that in the visible region.

8828-46, Session PWed

Tunable liquid crystal lens for a holographic projection system

N. Collings, Univ. of Cambridge (United Kingdom); Yi-Hsin Lin, Hung-Chun Lin, Ming-Syuan Chen, National Chiao Tung Univ. (Taiwan)

Experimental work confirms theoretical predictions for the LC lens in a holographic projection system

8828-47, Session PWed

An electrically tunable endoscopic system by adding a liquid crystal lens to enlarge and shift depth-of-field

Hung-Shan Chen, Yi-Hsin Lin, National Chiao Tung Univ. (Taiwan)

Conventional endoscopic systems consisting of several solid lenses suffer from a fixed and limited depth of field (DOF). For practical applications in throat or stomach diagnoses, we have to mechanically change the distance between the solid lenses of a lens module in order to change the focusing plane and DOF. In this way, the endoscopic systems are bulky. In 2011, S. Kuiper at. al., proposed a electrowetting-based liquid lens for capsule endoscopes to improve the focusing properties. However, the depth-of-field in the endoscope still needs to be discussed and designed. In this paper, an electrically tunable endoscopic system by adding a liquid crystal lens to enlarge and shift depth-of-field is demonstrated and discussed. The liquid crystal lens with an operation of two modes, positive and negative lenses, can not only extend but also shift the depth of field of the endoscopic system. The optical mechanism and limitation of the electrically tunable endoscopic system is discussed. We believe this study can be extended in the applications of industrial and medical endoscopes.

8828-48, Session PWed

An electrically tunable optical zoom system with separated focusing and zooming functions

Ming-Syuan Chen, Po-Ju Chen, Yi-Hsin Lin, National Chiao Tung Univ. (Taiwan)

An electrically tunable optical zoom system using liquid crystal (LC) lenses is important for many applications due to the advantages of light weight, low power consumption, and no mechanical moving elements. Recently, we have demonstrated the electrically tunable-focusing optical zoom system using two LC lenses and the optical mechanism is based on the concept of a confocal telescope. The object can be continuously zoom in and zoom out with object distance from 10cm to infinity. However, the focusing and zooming functions in the previous optical zoom system are not separable. The zoom ratio decreases with the objective distance. In this paper, we demonstrated an electrically tunable optical zoom system with separated focusing and zooming functions. The optical mechanism and design rules are discussed. The focusing distance and magnification of the image can be controlled separately by focusing LC lenses and zooming LC lenses. As a result, the zoom ratio is independent of objective distance and only depends on the tunable range of the lens power of the LC lenses. This study helps designing many applications with an optical zoom function, such as cell phones, cameras, holographic projectors and pico projectors.

8828-49, Session PWed

Beaming and filtering at terahertz frequencies in liquid crystal filled metallic grating

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The increasing interest of the scientific community in the terahertz frequency range is motivated by the unique property of sub-millimeter waves to penetrate any nonmetallic materials such as fabric and plastic, and sense objects distinctive signatures. Furthermore because of its low photon energy, terahertz radiation can be used in medical applications for accurate imaging without damaging tissues. For these reasons there is a growing need of devices dedicated to control the radiation in this frequency range. Current established technology uses non-tunable mesh-like filters and mechanical mirrors to filter and manipulate energy at these frequencies. We study electrically-controlled beaming and filtering abilities of sub-wavelength metallic gratings. The geometry consists of a finite array of metallic slits separated by spacers and filled with liquid crystal. We exploit the Fabry-Perot like resonances of the slits to filter THz radiation. An external voltage is then applied across the metallic grating in order to generate an electro-optic torque force on the liquid crystal molecules and change the dielectric constant inside the slits. This results in a large tuning effect on the Fabry-Perot resonances. We also show that a linear voltage distribution across the grating induces a linear phase delay and a beam-steering of terahertz radiation impinging at grazing incidence.

8828-50, Session PWed

Thermal degradation of the distributed-feedback cavity in cholesteric liquid crystal lasers

Andrii Varanytsia, Peter Palffy-Muhoray, Kent State Univ. (United States)

Cholesteric liquid crystals due to their birefringence and self-assembled periodic structure are known to form a distributed-feedback cavity and show mirrorless lasing. In this work, cholesteric liquid crystal laser emission was studied from two different liquid crystal hosts doped with the same laser dye. For both systems the lasing thresholds were measured and energy output was studied under a pump power significantly higher that lasing threshold. When the pump power was increased, a shift of lasing wavelength was observed. One of systems demonstrated a rapid decrease of emission after the pump energy reached a threshold value. This phenomenon was associated with thermal degradation of distributed-feedback cavity in cholesteric liquid crystal host caused by absorption of pump energy and heating. The local change of temperature of the host material can change the cholesteric liquid crystal pitch and shift the position of the selective reflection band. Further heating of the system can move the selective reflection band away from fluorescence of the laser dye and at some point the system loses the ability to lase. Emission from cholesteric liquid crystal lasers was studied at different pump powers and at different temperatures. From the obtained results, we were able to estimate the local increase of temperature of the cholesteric liquid crystal host caused by optical pumping. The estimated heating correlates well with study of temperature dependence of position of selective reflection band in cholesteric liquid crystal hosts.

8828-51, Session PWed

Effect of liquid crystal structures on liquid crystal based biosensor for cholic acid detection

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The concentration level of bile acids is a useful indicator for the diagnosis of liver diseases since individual suffering from liver diseases often has a sharp increase in bile acid concentration. Here we present a nematic liquid crystal (LC) based biosensor for the detection of cholic acid (CA). The orientations assumed by nematic LCs in contact with water are sensitive to the molecules at the LC/aqueous interface. The adsorption of sodium dodecyl sulfate (SDS) to the LC/aqueous interface resulted in homeotropic (untilted) LC alignment. Subsequent adsorption of CA to the SDS-laden interface resulted in a reorientation of the LC from homeotropic alignment to a tilted alignment. This transition took place above a certain concentration of CA, which we define as the detection limit of CA. By studying this system with nematic LC 4', 4-alkylcyanobiphenyls (nCB, n=5-8) where n is the alkyl chain length, we found the detection limit increases with the increase of chain length. Binary mixtures of nCB and other LCs were also studied. In general, the detection limit decreases with the increase of dipole moment. These studies pave the way for the optimization of LC-based biosensors in terms of the choice of LC material.

8829-1, Session 1

Efficient simplified OLEDs using high-work-function polymeric anodes *(Invited Paper)*

Tae-Hee Han, Su-Hun Jeong, Min-Ho Park, Seong-Hoon Woo, Tae-Woo Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

Organic light-emitting diodes (OLEDs) have potential applications in large area, full-colour, high resolution flat-panel displays, future flexible displays, and solid-state lighting. Although device efficiencies and operational lifetimes of vacuum-deposited small-molecule OLEDs have been significantly increased, state-of-the-art OLED device structures have been developed to have more functional layers than did earlier OLEDs. These functional layers facilitate charge injection, transport and blocking in the devices and thus to help balance injection and transport of holes and electrons to the emitting layer for efficient radiative recombination. Another important role of these functional layers in multilayered OLEDs is to prevent an exciton quenching near electrodes. The standard fabrication method for small-molecule OLEDs is vacuum deposition, which has high costs of materials and processing to fabricate multilayered structures, and so has been a critical impediment to mass production at a low cost. Therefore, achieving simple structured OLEDs while maintaining their original luminous current efficiency (CE) has become a major challenge that must be solved before wide industrial application of OLEDs can be economically feasible.

Our idea to simplify structure to realize highly efficient OLEDs that uses a molecularly-controlled, high-work-function hole injection layer (HIL) on the anode or high-work-function anode, which enable efficient blocking of exciton quenching as well as efficient hole-injection and efficient electron-blocking at the same time. Our HILs develops a gradient work function (WF) by self-organization of a perfluorinated ionomer in conducting polymer films (We call “GraHIL”). This single-layered small molecule OLED has much greater CE (~20 cd/A) than do standard multilayered small molecule OLED devices that use conventional well-known hole injecting small-molecule, as a HIL (CE ~12 cd/A). The dramatic improvement in simplified OLEDs is achieved because that molecularly controlled GraHIL meets all the requirements for realization of simplified small-molecule OLEDs. From our studies regarding exciton quenching, we find that the self-organized surface layer of our GraHIL having efficient hole-injection/electron-blocking capability can prevent the severe quenching of excitons at the HIL/emitting layer interface without needing a hole transporting layer. We extended our work to a new flexible polymeric anode material which has easy work-function tunability and thus makes ohmic-contact between the anode and an overlying organic layer even with a high ionization potential. We finally demonstrated indium-tin-oxide-free flexible solid-state lighting devices using white fluorescent OLEDs.

8829-2, Session 1

Efficient electroluminescence from heavy (Ir) and not so heavy (Cu) metal complexes *(Invited Paper)*

Mark E. Thompson, Valentina Krylova, Yifei Liu, The Univ. of Southern California (United States)

No abstract available.0

8829-3, Session 1

Highly efficient new emitting materials based on dual core concepts for blue fluorescence OLEDs *(Invited Paper)*

Beomjin Kim, Seungho Kim, Jaehyun Lee, Hwangyu Shin, The Catholic Univ. of Korea (Korea, Republic of); Daisuke Yokoyama, Junji Kido, Yamagata Univ. (Japan); Jongwook Park, The Catholic Univ. of Korea (Korea, Republic of)

New blue fluorescent emitting materials for OLEDs based on dual core concept were synthesized and TPAPTP exhibited higher quantum efficiency (7.51 %) without doping and 2 times longer life-time than MADN, the commercial material.

8829-4, Session 1

Materials design for highly efficient delayed fluorescence *(Invited Paper)*

Chihaya Adachi, Kyushu Univ. (Japan)

Although typical organic molecules are simply composed of carbon (C), hydrogen (H), nitrogen (N) and oxygen (O) atoms, carbon’s unique bonding manners based on sp3, sp2 and sp hybrid orbitals enable very complicated molecular architectures, leading to amazing functions in a wide variety of creatures and industrial products. In the last two decades, the allure of unlimited freedom of design with organic molecules has shifted a significant part of the research effort on electronics from inorganic into organic materials. In particular, great progress has been achieved in the development of organic light-emitting diodes (OLEDs). The successive progress of 1st generation OLEDs using fluorescent molecules and 2nd generation OLEDs using phosphorescent molecules solidified organic materials as a very attractive system for practical electronics.

In this study, we designed new advanced electroluminescent (EL) molecules composed of only conventional CHN atoms without any precious metals. With proper molecular design, the energy gap between the two excited states, i.e., singlet (S1) and triplet (T1) excited states, are minimized, promoting very efficient spin up-conversion from T1 to S1 states (reverse intersystem crossing (ISC)) while maintaining a rather high radiative decay rate of >106/s, leading to a very high fluorescence efficiency. Using these unique molecules, we realized a very high external EL efficiency that is comparable with those of high-efficiency phosphorescence-based OLEDs. Thus, these molecules harvest both singlet and triplet excitons for light emission under electrical excitation through fluorescence decay channels.

8829-5, Session 1

Novel host materials for blue phosphorescent OLEDs

Peter Strohriegl, Daniel Wagner, Pamela Schroegel, Sebastian Hoffmann, Anna Koehler, Univ. Bayreuth (Germany); Ute Heinemeyer, Ingo Muenster, BASF SE (Germany)

Phosphorescent OLEDs have attracted attention during the past years because of their ability to achieve nearly 100% internal quantum yield. Triplet emitters are doped in a host material to avoid concentration quenching and triplet-triplet annihilation. Matrix materials for blue phosphors are difficult to realize because a triplet energy of 2.8 eV or higher and efficient carrier transport have both to be realized.

We present two different classes of host materials. The first are

derivatives of the well known

CBP. By minimizing the conjugation through the central biphenyl unit in CBP by i) replacement of the biphenyl by a twisted 2,2' dimethylbiphenyl and ii) meta-substituted biphenyl units we were able to make efficient matrix materials for blue phosphors with triplet energies of more than 2.9 eV [1,2]. These materials were used as matrix for the carbene emitter Ir(dbfmi) with a pure blue emission at 450 nm.

The second class of matrix materials are donor-substituted triazines, in which the electron and hole transport are separated through a non-conjugated bridge to form a bipolar host material [3]. Density functional theory (DFT) calculations showed, that these materials are promising hosts for blue phosphors. The photophysical and electrochemical properties are reported. By a variation of the substitution pattern the thermal, morphological and electrochemical properties are tailored. With regard to the application as host material the energy transfer to phosphorescent blue emitters as well as blue phosphorescent OLEDs will be presented.

[1] P. Schroegel et.al., J.Mater.Chem. 21, 2266 (2011)

[2] P. Schroegel et.al., Org. Electr. 12, 2047 (2011)

[3] M. Rothmann et.al., Org. Electr. 12, 1192 (2011)

8829-6, Session 1

Novel oligonuclear copper complexes featuring exciting luminescent characteristics *(Invited Paper)*

Daniel M. Zink, D. Volz, Larissa Bergmann, Karlsruhe Institute of Technology (Germany) and cynora GmbH (Germany); Thomas Baumann, cynora GmbH (Germany); M. Nieger, Univ. of Helsinki (Finland); Hartmut Yersin, Univ. Regensburg (Germany); S. Bräse, Karlsruhe Institute of Technology (Germany)

In recent years, the research field of organic electronics has gained increasing interest due to its potential application fields such as organic light emitting diodes (OLEDs), organic photovoltaics (OPVs) and organic transistors. , , In the case of OLEDs for general lighting or displays, a substantial amount of research has been carried out on the development of new concepts and materials. Accordingly, tremendous improvements have been achieved by the use of luminescent triplet emitters, allowing for high efficiencies and color tunability. As a downside, however, these precious transition metals based on iridium, , , platinum, or ruthenium, are a costly commodity often due to their low availability. Therefore, more abundant and cost-efficient metals with d10-configuration such as Cu(I) or Ag(I) have received great attention as they offer a new path to efficient emitters by means of using both singlets and triplet excitons. Luminescent Cu(I) complexes, especially with their rich structural diversity and easy accessibility, allow for designing emitters with desired photophysical properties, such as the emission color while maintaining high efficiencies.

Various novel and highly luminescent mono- and oligonuclear copper complexes have been developed and synthesized by means of a modular ligand system of easily accessible chelating ligands, specifically those containing nitrogen and phosphorous. These novel complexes feature promising photoluminescence properties which can be easily tuned by changing the electronic characteristics of the appropriate ligands to cover the visible spectrum in the range of 480 to 690 nm. Additionally, high quantum yields, up to 95% in the solid state, have been reached.

8829-7, Session 1

Continuous synthesis of device-grade semiconducting polymers in droplet-based microreactors *(Invited Paper)*

James H. Bannock, Siva H. Krishnadasan, Adrian M. Nightingale, Chin Pang Yau, Kevin Khaw, Imperial College London (United Kingdom); Daniel Burkitt, Jonathan J. M. Halls, Solar Press (United Kingdom); Martin J. Heeney, John C. de Mello, Imperial College London (United Kingdom)

A method is reported for the controlled synthesis of device-grade semiconducting polymers, utilizing a droplet-based microfluidic reactor. Using poly(3-hexylthiophene) (P3HT) as a test material, the reactor is shown to provide a controlled and stable environment for polymer synthesis, enabling control of molecular weight via tuning of flow conditions, reagent composition or temperature. Molecular weights of up to 92 000 Da are readily attainable, without leakage or reactor fouling.

The method avoids the usual deterioration in materials quality that occurs when conventional batch syntheses are scaled from the sub-gram level to higher quantities, with a prototype five-channel reactor producing material of consistent molecular weight distribution and high structural order at a rate of ≈60 g/day. The droplet approach is especially well suited to the controlled synthesis of statistical and block co-polymers, providing greater control over stoichiometry than equivalent batch syntheses.

8829-8, Session 1

Efficient cyclometalated platinum complexes for displays and lighting applications *(Invited Paper)*

Jian Li, Arizona State Univ. (United States)

The white organic light emitting diodes (WOLEDs) with high power efficiency (>100 lm/W) are considered as strong candidates for next generation illumination devices. Especially, WOLEDs use environmentally benign organic materials and their fabrication cost can be significantly reduced with potential roll-to-roll processing technology. In this presentation, we will discuss some of our efforts towards the development of efficient WOLEDs, which include our progress on 1) excimer-based WOLEDs, 2) the development of deep blue halogen-free Pt-based phosphorescent emitters, 3) the efficient white OLEDs utilizing all Pt-based phosphorescent emitters, and 4) improve the light outcoupling efficiency by incorporating narrow band phosphorescent emitters in the microcavity device settings.

8829-9, Session 1

Conjugated polymer particles: towards self-assembling organic photonics *(Invited Paper)*

Alexander J. C. Kuehne, DWI an der RWTH Aachen e.V. (Germany)

Sub-micrometer structure formation is an intricate condition for high fidelity organic photonics. I will present various pathways towards batch preparation of monodisperse particles consisting entirely of conjugated polymer. These particles form colloidal crystals through energy-free self-assembly, resulting in large scale 3-dimensional photonic structures of high quality. (AJC Kuehne et al., Chem. Commun. 2011, 47, 12379; AJC Kuehne et al., Nature Commun. 2012, 3, 1088)

The monodisperse conjugated polymer particles are synthesized in a simple one-pot procedure, leaving the particles dispersed in a non-hazardous solvent . The samples can then be processed from dispersion, which allows customized processing by wet deposition techniques, such as ink-jet printing. After deposition, the solvent evaporates and the dispersed particles assemble into crystalline arrays due to capillary forces.

These opal photonic crystals exhibit a clear photonic-bandgap due to the periodicity of the particle array as well as luminescence from the individual conjugated polymer particles. Thus, the particles hold great promise for self-assembled filters, converters and resonator devices.

8829-10, Session 1

Electronic structure investigation of doping C60 with metal oxide *(Invited Paper)*

Chenggong Wang, Yongli Gao, Univ. of Rochester (United States)

Fullerene (C60) has been used extensively as an acceptor material in organic photovoltaic (OPV) cells. Other applications including n-channel organic thin film transistors (OTFT) and C60 based organic superconductors have been reported more than a decade ago. Ordinarily C60 behaves as a strongly n-type organic semiconductor with the lowest unoccupied molecular orbital (LUMO) close to the Fermi level. We have investigated p-doping of C60 with molybdenum oxide (MoOx) with ultra-violet photoemission spectroscopy (UPS), inverse photoemission spectroscopy (IPES) and atomic force microscopy (AFM). Both surface doping and bulk doping by MoOx are studied. It was found that the thermally evaporated MoOx inter-layer substantially increased the surface workfunction. This increased surface workfunction strongly attract electrons towards the MoOx layer at the C60/MoOx interface, resulting in strong inversion of C60. Energy levels of C60 relax gradually as the thickness of C60 increases. An exceptionally long (>400 Å) band bending is observed during this relaxation in C60. Such a long band bending has not been observed for other organic/MoOx interface. For the bulk doping, MoOx doping ratios from 1% to over 100% were investigated. The saturation occurs at ~20%, when the highest occupied molecular level (HOMO) of C60 starts to be pinned at the Fermi level. These studies demonstrate effective ways to manipulate the electronic structures of the fullerene.

8829-11, Session 2

Plasmonic photoinjection spectroscopy: unraveling charge carrier injection and transport directly in organic light emitting diodes *(Invited Paper)*

Noel C. Giebink, The Pennsylvania State Univ. (United States)

Current injection and extraction at a metal-organic semiconductor interface is central to the operation of all organic optoelectronic devices, strongly influencing the efficiency and performance of organic light emitting diodes (OLEDs), photovoltaics, and thin film transistors. Efforts to date have developed various working models aimed at describing injection in organic semiconductors, however, the goal of a comprehensive understanding has so far been complicated by the a lack of techniques capable of characterizing both the interface energetics and bulk electronic transport properties directly in an operating device.

Here, we exploit resonant coupling to the surface plasmon polariton (SPP) mode(s) of a metal contact to extend the method of internal photoemission and use it to investigate the injection process in various small molecule organic semiconductor devices. By measuring the injected current on and off resonance as a function of wavelength and external bias for sub-gap, near-infrared excitation, we determine the electron and hole injection barriers directly in OLED devices. As compared to conventional internal photoemission under free-space illumination, resonant coupling to an SPP mode affords three important advantages in application to organic semiconductors: an order of magnitude improvement in sensitivity, unambiguous differentiation between photoinjected current and spurious trap-state photoconductivity, and the capability to measure bulk time-of-flight mobility directly in sub-100 nm thick devices. This talk will focus on the development and application of this method to the commonly used OLED materials tris(8-hydroxyquinoline) aluminum (Alq3) and N,N'-diphenyl-N,N'-bis(1-naphthyl) -1,1'biphenyl-4,4" diamine (NPD) in conjunction with Ag, Au, and Al contacts.

8829-12, Session 2

Fundamental properties of vacuum-deposited amorphous organic semiconductor films: density, molecular orientation, and refractive index *(Invited Paper)*

Daisuke Yokoyama, Yamagata Univ. (Japan)

In OLEDs, amorphous organic semiconductor films are mainly used because they need to be driven under a high electric field uniformly applied to the thin devices. However, the fundamentals of electrical and optical properties of amorphous organic semiconductor films have not yet been elucidated sufficiently due to the complexity of higher-order structures of molecules in the amorphous films.

Although it is not easy to clarify the microscopic higher-order structures with randomness, we can obtain some macroscopic properties of the films from the results of experiments, some of which give us useful suggestive information on the "average" higher-order structures in the films. In this presentation, such informative macroscopic properties will be shown with systematic experimental results to discuss the fundamentals of structures and properties of vacuum-deposited amorphous organic semiconductor films.

The first property that we will focus on is the density of the films, which affects both of the electrical and optical properties of the films. We found that the density of vacuum-deposited amorphous organic films highly depends on materials [1]. This result shows us a critical difference of the properties between amorphous and crystalline films. Next, the second one is the optical anisotropy in the films, which is obtained by ellipsometry. From this property, we can discuss the molecular orientation. In addition to the orientation of molecular axis that have been reported previously [2], a detailed analysis of functional group orientation will be shown. Then, the third one is the refractive index. We have recently found that the refractive indices of amorphous organic semiconductor films can be widely controlled [3]. This refractive index control will be discussed with the variety of densities. We believe that the comprehensive analysis of these three properties leads to further understanding of the electrical and optical properties of the films and devices from a fundamental viewpoint.

[1] D. Yokoyama et al., submitted. [2] D. Yokoyama, J. Mater. Chem. 21, 19187-19202 (2011). [3] D. Yokoyama et al., Adv. Mater. 24, 6368-6373 (2012).

8829-13, Session 2

Degradation mechanisms of light emitting diodes revealed by time-resolved photoluminescence measurements *(Invited Paper)*

Hideyuki Murata, Atula D. Sandanayaka, Japan Advanced Institute of Science and Technology (Japan)

The intrinsic degradation in Alq3-based OLEDs is found to be caused by the photophysical degradation processes of NPD and Alq3 molecules in the vicinity of the NPD/Alq3 interface. We demonstrate that two degradation pathways with different time constants take place during a decrease in electroluminescence under constant current operation. From time-resolved photoluminescence measurements, we identify the first stage of the degradation in the luminescence decay curve as the decomposition of NPD molecules triggered by an electron injection followed by the creation of excited states of NPD. The second stage of the degradation with a longer time constant was due to the formation of a luminescent quencher in the emission zone, where the decomposition of Alq3 occurs by the reaction of Alq3 cation and water molecules.

8829-14, Session 2

Exciplex forming co-host as a platform for OLEDs with ultimate efficiency *(Invited Paper)*

Jang-Joo Kim, Young-Seo Park, Sunghun Lee, Seoul National Univ. (Korea, Republic of)

Phosphorescent organic light-emitting diodes (OLEDs) with ultimate efficiency in terms of the external quantum efficiency (EQE), driving voltage, and efficiency rol l-off are reported using an exciplex-forming co-host. This exciplex forming co-host system enables efficient singlet and triplet energy transfers from the host exciplex to the phosphorescent dopant because the singlet and triplet energies of the exciplex are almost identical. In addition, it allows low probability of direct trapping of charges at the dopant molecules and no charge injection barrier from the charge transporting layers to the emitting layer. By combining all these factors, the OLEDs achieved a low turn-on voltage of 2.4 V, a very high EQE of 29.1% and a very high power efficiency of 124 lm/W. In addition, the OLEDs achieve an extremely low efficiency roll-off. The EQE of the optimized OLED is maintained at more than 27.8% up to 10,000 cd/m2.

8829-15, Session 2

Emitter orientation as a tool to enhance OLED efficiency *(Invited Paper)*

Wolfgang Brütting, Tobias D. Schmidt, Bert J. Scholz, Christian Mayr, Lars Jäger, Univ. Augsburg (Germany)

Organic light-emitting diodes (OLEDs) are promising large-area light sources on their way to commercialization. However, there is still room for improvement in terms of light outcoupling efficiency and long-term stability under electrical operation.

The external quantum efficiency (EQE) of OLEDs is significantly less than 100% since only a small fraction of the consumed electrical power is converted into visible light that is finally extracted to air. Most of the efficiency loss is caused by suboptimal radiative quantum efficiency (RQE) of the emitting guest-host system and by dissipating a huge part of the radiated energy to optical modes such as surface plasmons or waveguided modes, which cannot easily be extracted by common outcoupling schemes. In order to increase the EQE of OLEDs new approaches are needed [1].

Recent studies show that light outcoupling can be enhanced considerably by horizontally oriented emitters; a feature that is well known for fluorescent emitters [2,3] and has lately been demonstrated in phosphorescent state-of-the-art OLEDs [4,5]. We identify non-isotropic emitter orientation by a thorough efficiency analysis of OLED stacks with systematically varied thickness [6]. We show that in order to achieve a consistent analysis, it is indispensable to account for possible deviations from randomness. Ignoring these orientation effects leads to a significant misinterpretation of the RQE and other factors, which determine the EQE of a device. Furthermore, state-of-the art emitter-matrix combinations will be used to demonstrate the potential for improving the efficiency of OLEDs in this way.

(1) Device efficiency of organic light-emitting diodes: Progress by improved light outcoupling, W. Brütting, J. Frischeisen, T.D. Schmidt, B. J. Scholz, C. Mayr, phys. stat. sol. A 44 (2013) 44-65, DOI 10.1002/pssa.201228320

(2) Determination of molecular dipole orientation in doped fluorescent organic thin films by photoluminescence measurements, J. Frischeisen, D. Yokoyama, C. Adachi, W. Brütting, Appl. Phys. Lett. 96 (2010) 073302

(3) Increased light outcoupling efficiency in dye-doped small molecule organic light-emitting diodes with horizontally oriented emitters, J. Frischeisen, D. Yokoyama, A. Endo, C. Adachi, W. Brütting, Organic Electronics 12 (2011) 809-817

(4) Oriented phosphorescent emitters boost OLED efficiency, M. Flämmich, J. Frischeisen, D.S. Setz, D. Michaelis, B.C. Krummacher, T.D. Schmidt, W. Brütting, N. Danz, Organic Electronics 12 (2011) 1663-1668

(5) Evidence for non-isotropic emitter orientation in a red phosphorescent organic light-emitting diode and its implications for determining the emitter's radiative quantum efficiency, T. D. Schmidt, D. S. Setz, M. Flämmich, J. Frischeisen, D. Michaelis, B. C. Krummacher, N. Danz and W. Brütting, Appl. Phys. Lett. 99 (2011) 163302

(6) Non-isotropic emitter orientation and its implications for efficiency analysis of organic light-emitting diodes, T.D. Schmidt, M. Flämmich, B.J. Scholz, D. Michaelis, C. Mayr, N. Danz, W. Brütting, Proc. SPIE 8435 (2012) 843513

8829-16, Session 2

Performance improvement of fluorescent blue organic emitting diode by insertion buffer layer between hole-transporting layer and emitting layer

Bumsung Lee, DS Hi-Metal Co., Ltd. (Korea, Republic of)

The efficiency improvement of fluorescent blue organic light-emitting diodes with buffer layer, were investigated by inserting buffer layer which has lower HOMO energy and lower hole mobility than HTL material, between interface of HTL and EML. The inserted buffer layer (HOMO, -5.70 eV) could control the effective hole injection by decreasing energy barrier between HTL (-5.58 eV) and EML (5.96 eV) and also change the recombination zone, resulting to better electron-hole balance. To investigate working principle such as the electron-hole balance, several buffer materials which have different HOMO energy and hole mobility were used as a buffer layer and also the movement of recombination zone was measured by doping controlled device, in which blue and red dopant were used at different thickness zone to measure hole-electron recombination ratio. Based on the the result, It was found that the insertion of buffer layer which has lower HOMO energy and lower hole mobility can make effective recombination zone and this can lead to high performance.

8829-17, Session 2

Charge transport and injection into triarylamine copolymers from solution processed metal oxide contacts *(Invited Paper)*

Stephen M. Logan, Jenny E. Donaghey, Imperial College London (United Kingdom); Weimin Zhang, Imperial College London (United Kingdom) and Guangxi Univ. for Nationalities (China); Iain McCulloch, Alasdair J. Campbell, Imperial College London (United Kingdom)

Triarylamine copolymers are air stable, amorphous organic semiconductors with versatile applications as active layers in Organic Light Emitting Diode (OLED) and Thin-Film Transistor (TFT) devices. In particular, incorporation of a bridged fluorene unit to create poly(fluorene-co-triarylamine) (PF-TAA) has been shown to yield mobility values in TFTs as high as 10-2 cm2/Vs and contribute to recorded mobilities in excess of 5 cm2/Vs in small molecule-polymer blends. The application relevant performance of PF-TAA as a blue light-emitting polymer has led to its commercial availability for use as the active layer in solution processed OLEDs.

Given the importance of these materials we have employed chemical design strategies to create a novel silafluorene bridged triarylamine; poly(silafluorene-co-triarylamine) (PSiF-TAA). Using time-of-flight transient spectroscopy (TOF) we present findings of a systematic study of bulk hole mobility in these materials. PSiF-TAA (mobility = 3.1x10-3 cm2/Vs at field 0.7x105 V/cm) shows a five-fold improvement in bulk hole mobility over that of PF-TAA.

Leading on from our study of charge transport we investigate charge injection into the polymers from three recently reported solution-processable metal oxide hole-injecting contacts. Under ambient conditions, we solution process molybdenum trioxide (MoO3), vanadium pentoxide (V2O5) and chlorinated-indium tin oxide (Cl-ITO) injecting contacts and use current-density - voltage space charge limited current analysis (SCLC) to quantify the charge injection efficiency into PF-TAA and PSiF-TAA.

On analysis of TOF and SCLC data we undertake to elucidate mechanisms of charge transport and injection that contribute to performance in TFT and OLED devices.

8829-18, Session 2

Measuring and modeling exciton recombination in organic light-emitting devices *(Invited Paper)*

Nicholas C. Erickson, Russell J. Holmes, Univ. of Minnesota, Twin Cities (United States)

The realization of high efficiency in organic light-emitting devices (OLEDs) requires the effective formation and confinement of excitons. Often, this confinement occurs through the use of a multilayer device architecture that employs both charge and exciton blocking layers. Recently, there has been an increase in the use of emissive layer architectures that contain mixtures or gradients of hole- and electron-transporting materials that are uniformly doped with a phosphorescent guest. Such structures have been used to efficient device operation, and in the case of graded emissive layers (G-EML), efficient single-layer OLEDs. In this work we demonstrate an experimental approach to determine the spatial extent and location of exciton recombination in a wide variety of OLED structures. We find that structures based on mixed and graded emissive layers have significantly broader exciton recombination zones than conventional devices based on planar heterostructures. The location of exciton recombination in an OLED is an important design parameter that strongly determines device efficiency. In particular, the spatial extent of exciton recombination can impact exciton quenching, particularly under high excitation. In the case of the G-EML device architecture, an electronic model is developed to predict the location and extent of the exciton density profile by considering the drift, diffusion, and recombination of charge carriers within the device. It is found that the location and extent of the exciton recombination zone may be tailored using the G-EML architecture, allowing for the realization of simple, single-layer devices with high-brightness, high-efficiency operation.

8829-19, Session 2

High-efficiency P-OLEDs: analysis and progress *(Invited Paper)*

Matthew Roberts, Cambridge Display Technology Ltd. (United Kingdom)

The efficiency of organic LEDs continues to rise, and as the technology advances the efficiency limits continue to be pushed beyond traditional limits. For fluorescent blues (singlet recombination), external quantum efficiencies >10% are now achievable without outcoupling enhancements [1], with triplet-triplet annihilation clearly demonstrating a route to minimizing triplet losses. For phosphorescent materials (triplet recombination), external quantum efficiencies in the range 20-25% are now routine without outcoupling enhancements, and recent observations of anisotropy in phosphor dipole alignment gives a potential route to increasing this even further [2]. Robust models of material and device factors limiting P-OLED efficiency are crucial to achieving further advances. This paper is organized as follows; Section 2 outlines the key factors determining P-OLED efficiency, and methods for characterising these parameters. Section 3 gives a comparative analysis of a previous and improved generation of RGB materials sets, showing which material parameters have given rise to advances in efficiency. Section 4 highlights further enhancements in performance attainable for display applications using a model microcavity device structure. Conclusions and current materials performance are summarised in Section 5.

8829-20, Session 2

Charge-transporting materials using quasi-planar structure as a key scaffold *(Invited Paper)*

Atsushi Wakamiya, Hidetaka Nishimura, Tatsuya Fukushima, Yasujiro Murata, Hironori Kaji, Kyoto Univ. (Japan)

The development of excellent charge-transporting materials with high charge carrier mobility is a crucial issue to achieve high performance in organic-device applications including organic light-emitting diodes (OLEDs). As a new π-conjugated skeleton for charge-transporting materials, we focused on partially bridged triphenylamine structure, in which three phenyl groups are constrained in a quasi-planar fashion with two oxygen-bridges. As model compounds, we synthesized a series of oxygen-bridged triphenylamine dimers 1–4. X-ray crystal structural analysis revealed that all of the dimers 1–4 form one-dimensional on-top π-stacking with intermolecular distances of 3.72–3.79 Å. Time resolved microwave conductivity (TRMC) measurements on the crystals of 2 showed the charge carrier mobility in the on-top π-stacking direction (1.72 cm2/Vs) was higher than those in the other directions (0.45–0.51 cm2/Vs). Anisotropic charge carrier mobility was also observed in the vacuum deposited amorphous film of 2; the carrier mobility in the perpendicular direction to the substrate (2.85 cm2/Vs) was higher than that in parallel (0.93 cm2/Vs), suggesting horizontal molecular orientation of 2 on the substrate. Time-of-flight (TOF) measurements on the vacuum-deposited amorphous film of 1–3 also showed good hole-transporting properties (1: 0.8 ? 10–3 cm2/Vs, 2: 1.7 ? 10–3 cm2/Vs, 3: 2.5 ? 10–3 cm2/Vs), suggesting the potential use of these materials as hole-transporting materials in organic devices.

8829-21, Session 2

Inverted top-emitting organic light-emitting diodes with high current efficacy *(Invited Paper)*

Bernard Kippelen, Keith A. Knauer, Ehsan M. Najafabadi, Wojciech Haske, Michael P. Gaj, Kendall C. Davis, Canek Fuentes-Hernandez, Ulises Carrasco, Georgia Institute of Technology (United States)

Inverted top-emitting green, blue, and red electrophosphorescent OLEDs are demonstrated with low turn-on voltages, high current efficacies, and high maximum values of luminance. The devices contain an electron-injecting cathode consisting of aluminum coated with lithium fluoride. Optimized green devices with a phosphorescent emitter of tris(2-phenylpyridine)iridium(III) (Ir(ppy)3) are demonstrated on flexible glass, polyethersulfone substrates, and large-area polyethylene terephthalate substrates. When an N,N'-Di-[(1-naphthyl)-N,N'-diphenyl]-(1,1'-biphenyl)-4,4'-diamine (?-NPD) optical outcoupling layer is deposited on the anode the device has a turn-on voltage of 3.4 V and current efficacies of 108.0 cd/A at a luminance of 114.0 cd/m2 and 95.6 cd/A a luminance of 1463.4 cd/m2. Optimized blue devices with an emitter of iridium(III)bi[(4,6-di-fluorophenyl)-pyridinato-N,C2']picolinate (FIrpic) have a turn-on voltage of 3.3 V and achieve current efficacies of 39.9 cd/A at 137.6 cd/m2 and 32.9 cd/A at a luminance of 1012.2 cd/m2. Red devices with an emitter of tris[2-phenyl-4-methylquinoline]iridium(III) Ir(Mpqh)3 have a turn-on voltage of 3.6 V and current efficacies of 12.0 cd/A at 149.1 cd/m2 and 8.9 cd/A at 1,100.1 cd/m2.

8829-22, Session 2

Analysis of hole mobility of fluorene derivative films based on the Disorder Model and relationship between disorder free mobility and reorganization energy in the Marcus theory

Masanao Era, Saga Univ. (Japan); Kento Mori, Ryoka Systems Inc. (Japan); Norio Tomotsu, Idemitsu Kosan Co., Ltd. (Japan)

Development of organic semiconductor with high carrier mobility is indispensable to attain high performance organic electronic devices. For example, organic light-emitting diode is driven in space charge limited (SCLC) region. In this region, electronic current is according to the following equation, JSCLC is proportional to carrier mobility. This relationship implies that employment of high carrier mobility organic semiconductor lowers the driven voltage and enhances the light emission power efficiency.

In this work, we examined temperature and electric field dependencies of two fluorine derivatives which we reported previously that they have high hole mobility, and typical hole-transporting material, 4,4'-bis[N-(p-tolyl)-N-phenyl-amino] biphenyl (TPD) and 4,4'-Bis(carbazol-9-yl)biphenyl (CBP). The experimental data was analyzed according to the Gaussian Disorder Model. Then, we evaluated their non-disorder mobility, energetic disorder distribution, and specific disorder distribution . In addition, their reorganization energy was evaluated by a quantum mechanical calculation with ADF (Amsterdam Density Functional package, Scientific Computing & Modeling Co.) based on the Marcus theory.

The experimental and calculation results demonstrated that the non-disordered mobility has good proportionality relation with reorganization energy. Because the non-disordered mobility mean as a rough standard of carrier-transporting, this result suggest that evaluation of reorganization energy is a promising approach to design molecular structure of carrier transporting materials with high carrier mobility.

8829-23, Session 2

Investigation of the opto-electronic processes in a near-infrared OLED based on a squaraine dye-doped polymeric matrix

Benedikt Stender, Sebastian F. Völker, Christoph Lambert, Julius-Maximilians-Univ. Würzburg (Germany); Jens U. Pflaum, Julius-Maximilians-Univ. Würzburg (Germany) and Bavarian Ctr. for Applied Energy Research E.V. (Germany)

The field of organic light-emitting diodes (OLEDs) has been investigated intensively during the past two decades. In particular, solution processed polymer devices have gained increasing interest due to their tunable emission range in combination with low-cost, large-area fabrication. Whereas OLEDs emitting in the visible have launched the market, electroluminescent devices emitting in the near-infrared (NIR) are still at an immature state despite their potential for application in optical communication and their ability of room temperature operation . A major drawback of bare organic NIR-emitters is their tendency of degradation caused by the extended ?-conjugated electron system. To cope with this challenge a novel organic host-guest system consisting of the squaraine dye monomer M embedded in a SY-PPV polymer matrix has been investigated. Comparative studies of the steady-state photo- and electroluminescence provide access to the opto-electronic processes on molecular length scales. Optical excitation reveals an efficient energy transfer from the visible to the NIR emission range at 750 nm for doping concentrations of less than 2.0 wt.%. The associated Förster radius of 4.0 nm agrees very well with experimental data and confirms the model characters of the squaraine doped SY-PPV host. In case of electrically driven NIR-emission a power efficiency of 1.6 lm/W together with a turn-on voltage of 2.0 V has been achieved already at a doping level of only 0.05 wt.%. Therefore, NIR emission in this system is controlled by charge carrier dynamics rather than by exciton transfer and highlights its potential for opto-electronic applications.

8829-24, Session 3

Influence of charge transfer-induced molecular orientation on charge injection and transport of organic devices *(Invited Paper)*

Toshinori Matsushima, Hideyuki Murata, Japan Advanced Institute of Science and Technology (Japan)

Dramatic improvement of performance of OLEDs has been obtained upon inserting a transition metal oxide film between an electrode and an organic film or doping of an organic film by transition metal oxide. Several years ago we found that insertion of a very thin layer of 0.75 nm MoO_3 between ITO and NPD led to formation of an Ohmic contact at an ITO/NPD interface. This optimized MoO_3 thickness of 0.75 nm was much smaller than that ever reported. The Ohmic contact formed by the 0.75 nm MoO_3 layer allowed a driving voltage and long-term operational stability of OLEDs to be markedly improved. Also we succeeded in observing a clear SCLC of NPD and estimating hole mobility of NPD from the SCLC analysis. The estimated hole mobility somehow increased as NPD thickness was increased. In this opportunity we will discuss mechanisms of the Ohmic contact formation and the increased hole mobility together with our previous results mentioned before. From our recent results we find that the Ohmic contact formation is due to charge generation from the MoO_3/ NPD interface as well as a horizontal orientation of NPD molecules near a MoO_3 surface. Moreover the increased hole mobility is attributed to a gradient structure of NPD film density formed normal to a substrate plane.

8829-25, Session 3

Organic biluminescence: highly efficient, simultaneous emission from singlet and triplet states of purely organic materials *(Invited Paper)*

Sebastian Reineke, Massachusetts Institute of Technology (Germany)

Organic semiconductors possess two fundamental excited states, namely the singlet (S1) and triplet (T1) states, which are differentiated by their total spin, i.e. either 0 or 1, respectively. Efficient photoluminescence (fluorescence) can occur from the singlet state where the relaxation conserves spin. Luminescence from the triplet state (phosphorescence) is, if observed at all, very weak because it involves a spin flip, which is quantum mechanically forbidden. Still, triplet states play a determining role in the vast of organic-based optoelectronic applications including lasers, photovoltaic cells, and light-emitting diodes. At room temperature, phosphorescence from purely organic molecules is considered a lab curiosity and has only been observed in crystals with strict chemical requirements and under special conditions in soft matter. In this talk, I will discuss highly efficient, simultaneous fluorescence and phosphorescence from a single, purely organic molecule. The share of both intensities is determined by the intersystem crossing between S1 and T1. Phosphorescence is easily observed at room temperature for various, archetypical materials, which is a result of a greatly reduced non-radiative rate for the triplet. As one exemplar application, I will demonstrate that the triplet state of a purely organic molecule can participate in Förster resonant energy transfer (FRET) to a singlet state of an acceptor molecule – turning the donor into a source for dual FRET. The unique potential of organic molecules to function as a dual state emitter opens new fields of applications including the use as ultra-broadband emitters, optical sensors and attenuators, and effective intermediates for energy transfer.

8829-26, Session 3

Novel technologies for commercialized 55-inch WRGB OLED TV *(Invited Paper)*

Yoon-Heung Tak, Chang-Wook Han, Hyo-Seok Kim, Bong-Chul Kim, Jong-Woo Kim, Tae-Seung Kim, Bum-Sik Kim, Chang-Ho Oh, Su-Yeol Cha, Byung-Chul Ahn, LG Display (Korea, Republic of)

World's first commercialized 55-inch WRGB OLED TV has been developed and launched recently. Large-sized OLED displays require novel technologies to realize mass production. We will introduce commercialized 55-inch WRGB OLED TV and its novel technologies including oxide TFT, WOLED, solid phase encapsulation, and compensation technologies. Commercialized 55-inch WRGB OLED TV was fabricated by employing oxide TFT, color refiner, WOLED, and SPE. Oxide TFT and color refiner were fabricated on Gen. 8 glass substrate. WOLED was fabricated by the in-line evaporation process at the ? Gen. 8 production line. After all processes, solid phase encapsulation was covered on WOLED. Commercialized 55-inch OLED TV employs WRGB sub-pixel technology, while conventional OLED TVs have only 3 RGB sub-pixels. Additional white sub-pixels to RGB sub-pixels reduce power consumption. White OLED of WRGB sub-pixel technology emits white light and this light passes through RGB color refiner to produce red, green, and blue emission. Two stacked tandem WOLED structure is evaporated a fluorescent blue stack, a charge generation layer, and a phosphorescent YG stack in series. Solid phase encapsulation is adopted a barrier layer deposited by plasma chemistry composed of Si-based materials on OLED devices. The barrier layer prevents OLED devices from degradation by humidity and mechanical damages. We will introduce an external compensation technology to solve the issues of internal compensation pixel circuit.

8829-27, Session 3

Reliable 6 PEP LTPS device for AMOLED's *(Invited Paper)*

Cheng-Wei Chou, Pei-Yun Wang, Chin-Wei Hu, York Chang, Ching-Sang Chuang, Yu-Hsin Lin, AU Optronics Corp. (Taiwan)

Active matrix organic light-emitting diode (AMOLED) display have attracted great attention as the next-generation display because of its outstanding advantages such as superior color performance, low power consumption and high contrast. To fabricate an AMOLED display product, a stable thin film transistor technology is required. Among the transistor materials, low temperature poly silicon (LTPS) is the most stable material for AMOLED display application. However, high manufacturing cost from LTPS TFT's complicated process steps is the main issue which limited its development in AMOLED displays. To overcome the disadvantages of LTPS TFT, reducing the amounts of the photo processes are the most critical action to achieve the cost competitiveness in AMOLED display markets.

More than 8-photo-Lithography processes were generally used to fabricate the LTPS based AMOLED display. A novel LTPS based 6 masks TFT structure for bottom emission AMOLED display is demonstrated in this paper. This structure is the first report as far as we know. 6-masks TFT structure can fabricated with the traditional TFT-LCD array instruments and recipes without tuning other new process steps. High field effect mobility (PMOS > 80 cm2/Vs) and high reliability (PBTS ?Vth< 0.02V @ 50oC VG=15V 10Ks) was accomplished without the high temperature and rapid thermal annealing (RTA) activation process. Furthermore, the LTPS based 6 photo processes 14" HD bottom emission AMOLED displays were achieved using the Gen. 3.5 mass production factory. These results demonstrate that the LTPS based 6 photo processes TFT can be executed in large size AMOLED display for mass production.

8829-28, Session 3

Enhancing the efficiency of organic light-emitting diodes through interzone and intrazone energy transfer *(Invited Paper)*

Yi-Lu Chang, Univ. of Toronto (Canada)

Considerable progress has been made on organic light emitting diodes (OLEDs) over the past decade. This has made the commercialization of active-matrix OLED displays for mobile phones and even large-area flat panels possible recently. However, in terms of solid-state lighting, further reduction in electrical energy consumption is highly desired to make the technology viable to the lighting industry and compete with its inorganic LED counterpart. To improve the energy efficiency, significant work has been focused on the use of a variety of device architectures including insertion of an exciton confining or carrier blocking layer, doping the transport layers, as well as employing multiple emissive zone structures (same dopant in multiple hosts) in a single device. While effective, these designs are quite inconvenient for large-scale commercial applications. In this work, we have developed two simple ways to enhance the efficiency of OLEDs through intrazone and interzone energy transfer. High external quantum efficiencies (EQEs) of ~19.3% and ~21.0% were achieved at 1,000 cd/m2 for red OLEDs using these two approaches, respectively, which are among the best performances reported to date for red OLEDs. Detailed comparisons between the two simple yet effective methods will be presented.

8829-29, Session 3

Probing film structure of organic light-emitting diodes with neutron reflectometry *(Invited Paper)*

Paul L. Burn, Ian R. Gentle, Arthur R. G. Smith, Paul Shaw, Jake McEwan, The Univ. of Queensland (Australia); Michael James, Australian Synchrotron (Australia)

Advances in light-emitting materials design and manufacturing have brought the first organic light-emitting diodes (OLEDs) to market. For all the devices the structure of the layers plays an important role in controlling their opto-electronic and device properties. Neutron techniques such as neutron reflectometry (NR) and small angle neutron scattering are important methods for studying the physical structures of (macro)molecules and their interactions in solution and/or the solid state. We have been using an in situ photoluminescence-NR measurement for elucidating the relationship between physical structure and emissive properties. In this presentation we discuss structures comprised of phosphorescent iridium(III) complexes. OLEDs containing iridium(III) complexes are highly efficient but achieving this efficiency usually involves diluting the emissive complex in a host material such as 4,4'-bis(N-carbazolyl)biphenyl and having multilayer structures. We will report our study on the effect of thermal annealing on multilayer OLED structures.

8829-30, Session 4

Solution processable small molecular host materials for blue and white phosphorescence OLEDs *(Invited Paper)*

Chin-Ti Chen, Academia Sinica (Taiwan); Yi-Ting Lee, Academia Sinica (Taiwan) and National Taiwan Univ. (Taiwan); Yung-Ting Chang, Academia Sinica (Taiwan); Chao-Tsen Chen, National Taiwan University (Taiwan)

A new series of CzPX small-molecule host materials for blue phosphorescence OLEDs have been characterized. These CzPX

materials are truly amorphous and their triplet state energy are high in the range of 2.58~2.73 eV, estimated from the time-gated low temperature photoluminescence spectra of the neat film. Corresponding solution processed active single layer in blue phosphorescence OLEDs has been achieved. These devices have shown peak current efficiency at 7~11 cd/A, surpassing ~6 cd/A acquired for SimCP2-molecular host-based device with same fabrication condition. The results of hybrid white OLEDs based on CzPx small-molecular host will be presented as well.

8829-31, Session 4

Highly efficient and multilayered phosphorescence OLEDs fabricated by solution-process *(Invited Paper)*

Yong-Jin Pu, Yamagata Univ. (Japan)

Multilayered organic light emitting devices (OLEDs) are difficult to be fabricated by solution-process because of similar solubility of materials in each layer. When sping coating of an electron-transporting material onto an emitting layer, a host material and an emitting dopant have to be insoluble to the coating solvent of the upper layer. We synthesized phenylcarbazole-type host materials with high molecular weight, showing controlled solubility to organic solvents for the coating. Coating solvents of the electron-transporting layer were also optimized not to dissolve the host and emitting dopant. We fabricated all-solution-processed green phosphorescence OLEDs, in which only electrodes were formed in vacuum, consisting of the four layers: hole-injection layer, hole-transporting layer, emitting layer, and electron transporting layer. High efficiencies of 53 lm/W, 76 cd/A, and 21%EQE at 100 cd/m2 were achieved without outcoupling. This is one of best efficiencies ever reported in solution-processed green OLEDs.

8829-32, Session 4

Recent progress in the development of solution processable materials for solid-state lighting *(Invited Paper)*

Olivier P. Gaudin, Jonathan F. Maunoury, Enrico Orselli, Dominique Bascour, Jean-Pierre Catinat, Solvay S.A. (Belgium); Neetu Chopra, Jing Wang, Christophe Grenier, Venkataramanan Seshadri, Christopher T. Brown, Mathew K. Mathai, Plextronics, Inc. (United States)

Lighting accounts for approximately 20% of the worldwide electrical power consumption, so that there is an increasing need for developing high efficiency lighting products. Organic light emitting diodes (OLEDs) have the potential to provide both efficient and low cost light sources which could be used to replace conventional lighting technologies. In addition, OLEDS can be produced in the form of diffuse, large area and flexible lighting tiles, thus enabling entirely new lamp designs.

Alongside vacuum processing, which typically yields highly efficient and long lifetime devices, deposition of the OLED layers can also be achieved using solution processing. The latter offers the advantage of being compatible with low cost, high throughput, printing techniques, such as roll-to-roll (R2R) processing on flexible substrates. However, solution processed OLEDs tend to lag behind their vacuum counterparts in term of efficiency and lifetime.

Solvay and its partner Plextronics have developped a set of solution processable organic materials which can be used for the fabrication of partially solution processed white OLEDs having both high efficiency and long lifetime. This presentation will outline Solvay's approach to the development of white OLEDs for lighting, where several layers are solution processed. As the Solvay materials can be both vacuum and solution processed, a direct comparison of the device performance as a function of the material deposition technique used can be achieved.

8829-33, Session 4

Solution processed, blue phosphorescent small molecule organic light emitting diodes comprising metal oxide buffer layers *(Invited Paper)*

Stefan Hoefle, Uli Lemmer, Alexander Colsmann, Karlsruher Institut für Technologie (Germany)

Today, organic light emitting diodes (OLEDs) and displays have achieved commercial relevance due to their unique contrast and low power consumption. While most state-of-the-art OLEDs for OEM applications are deposited in vacuum, science and industry work hard on solution processable and hence potentially low-cost fabrication alternatives. The main objectives are to overcome solvent limitations during the deposition of multi-layer devices and to enhance the lifetime of the devices. One material class that was proven to be very beneficial for (vacuum deposited) OLEDs are transition metal oxides. In this work we use a variety of metal oxide precursors in order to fabricate charge carrier transport layers from MoO3 or WO3 for OLEDs from solution. The respective layers are transparent to visible light and become insoluble to most solvents after deposition enabling the subsequent deposition of almost any emitters. In particular we have focused on processes that can be carried out at moderate temperatures to be suitable for roll-to-roll fabrication on flexible plastic substrates. While most precursors require oxygen to be converted into a metal oxide, we investigated processes that can be carried out under nitrogen atmosphere and hence can be beneficial for the device lifetime. By using metal oxides with very high work function, we were able to fabricate efficient phosphorescent blue emitting OLEDs from solution as holes could easily be injected into the low HOMO of the emitter matrix.

8829-34, Session 4

Bright blue all solution processed multi-layer polymer light emitting diodes realized by thermal layer stabilization and orthogonal solvent processing

Emil J. W. List, Technische Univ. Graz (Austria) and NanoTecCenter Weiz Forschungsgesellschaft mbH (Austria)

To extend solution processed polymer light emitting device (PLED) technology from lab- to full production scale significant improvements in the material performance have to be devised. In addition it is necessary to adapt material and device concepts to solution based roll-to-roll fabrication processes. Only if similar performance values as achieved for organic light emitting devices (OLEDs) fabricated based on vacuum vapor deposition techniques can be realized, the benefit of cost effective and high throughput fabrication based on solution processing can reach its full potential for large area (flexible) devices, signage and lighting applications. Yet, to achieve the necessary requirements of high brightness values in the device, alongside with high efficiency and stable operation, OLEDs require balanced charge carrier injection and charge carrier transport as typically realized only in multilayer device structures. In this contribution we report on fully solution processed doulbe and triple-layer PLED assemblies that combine a hard bake process – to insolubilize the bottom hole transporting layer (HTL) - and the deposition of polymers from orthogonal solvents for both the emissive layer (EML) and optionally the deposition of additional the electron transport layer (ETL). The successful implementation of two different solution based multilayer approaches – based on orthogonal solvents and thermal stabilization of a polymeric layer - for several sequential spin-coating and annealing steps without harming the preceding layer is investigated and proven by atomic force microscopy (AFM) investigations. In addition ultraviolet photoemission spectroscopy (UPS) measurements evidence that the combination of materials and their assembly in PLEDs, as presented in this work, exhibit a favourable energy level alignment, i.e., efficient electron blocking at the HTL/EML-interface and hole blocking at the EML/ETL-interface. This allows for good charge carrier confinement within the EML resulting in an enhancement of the maximum luminance and electroluminescence efficiency for multilayer PLEDs in comparison to single layer devices. As it will be shown such solution processed PLED-stack exhibit highly efficient high brightness state of the art deep blue electroluminescence emission clearly demonstrating the potential of the presented concept.

8829-35, Session 5

The development of HIL and HTL inks for OLED application *(Invited Paper)*

Jing Wang, Christopher T. Brown, Christophe Grenier, Mathew K. Mathai, Venkataramanan Seshadri, Neetu Chopra, Darin W. Laird, Christine McGuiness, Jian Wang, Sergey B. Li, Plextronics, Inc. (United States)

OLED technology has advanced rapidly in recent years, especially with respect to organic materials, color patterning, electronic driving methods, and encapsulation. While OLED has become a mass-market technology in small/medium displays the expected investments in new fabs indicate the growth will continue with increasing competition and will likely include larger size applications. Today, nearly all AMOLED displays are made using thermal evaporation which often yields a low material utilization, and is limited to smaller substrate sizes. Cost-Effective production of OLED displays requires a transition from all vapor manufacturing to one with solution printing processes.

Over the last few years Plextronics Inc. has been developing solution processing material and ink systems with a focus on materials and inks for hole injection (HIL, both aqueous and non-aqueous) and hole transport layers (HTL). We will report on recent developments that enable solution processed OLEDs with state-of-the-art device performance.

8829-36, Session 5

Recent advances in ITO-free SMOLEDs and polymer guest: small-molecule host devices *(Invited Paper)*

Joseph Shinar, Ruth Shinar, Min Cai, Rui Liu, Emily Hellerich, Zhuo Ye, Kai-Ming Ho, Rana Biswas, Jeremy Intemann, Malika Jeffries-El, Iowa State Univ. (United States)

Extremely efficient ITO-free SMOLEDs and polymer guest:small-molecule host devices will be reviewed. The former are due, in large part, to a microcavity effect. And although numerous extensive studies of guest-host OLEDs with a polymer or small molecule host and small molecule guests have been reported, such extensive studies on devices with a small molecule host and a polymer guest are lacking. Results on such guest-host devices with a CBP host and polymer (including newly synthesized) guests, will be described, including stability of such devices that has not been reported.

8829-37, Session 5

High efficiency in solution processed blue and white phosphorescent organic light-emitting diodes *(Invited Paper)*

Jun Yeob Lee, Ho Jong Kang, Oh Young Kim, Chil Won Lee, Yong Joo Cho, Kyoung Soo Yook, Dankook Univ. (Korea, Republic of)

High efficiency solution processed blue and white phosphorescent organic light-emitting diodes were fabricated by developing novel device architecture and soluble materials. Alcohol soluble host and dopant materials were synthesized to prepare multilayer device structure by solution process and high efficiency could be achieved in blue and white phosphorescent organic light-emitting diodes. In addition, several asymmetric host materials were synthesized for smooth amorphous film formation and high efficiency above 20% could be realized in blue phosphorescent organic light-emitting diodes.

8829-38, Session 5

Distinctive characteristics of solution processed OLEDs: physical studies *(Invited Paper)*

Denis Kondakov, Weiying Gao, Adam Fennimore, Shiva Prakash, DuPont (United States); Marc Sims, Ines Wyrsta, Ian D. Parker, DuPont Displays (United States)

Arguably, solution-processing of the emissive layer (EML) is the most desirable capability of OLED fabrication process because it replaces expensive FMM (fine metal mask) patterning step for RGB displays. Aside from the manufacturing advantages, there are multiple consequences to solution processing the EML.

Intermixing between HTL and EML is an important factor that requires a proper control through materials and process design. It may or may not be detrimental to device performance, depending on the particular OLED. For example, it is well known that in some evaporated devices an intentional admixing of the HTL component throughout the EML yields a specific advantage such as increased device lifetime or efficiency. In solution-processed devices, mixing is defined by a presence of a region where EML and HTL molecules coexist. Location and composition of such a region is determined by particular details of solution processing and has important performance implications. We applied techniques such as impedance spectroscopy, photoemission spectroscopy (UPS and XPS), and emission zone profiling with combined solution/vapor EMLs and HTL-EML exciplex formation as a marker to determine extent and properties of mixed layer.

Another consequence of solution processing is a different molecular ordering compared to that in evaporated layers. In a number of cases we have examined, the act of solution processing results in an isotropic molecular orientation in the film, whereas evaporated films are often dominated by a strong anisotropic orientation, with an increased number of parallel (or in-plane) transition dipoles and, consequently, higher light outcoupling and electroluminescence efficiency.

Although not an inherent to solution processing, solvent entrapment is a common consequence and may affect the performance of OLEDs. Using headspace gas chromatography/mass spectroscopy to quantify the amount of solvent entrapped, we have observed its effect on the device lifetime.

8829-39, Session 5

Metal oxide for solution-processed small molecule phosphorescent light emitting diodes

Franky So, Shuyi Liu, Rui Liu, Univ. of Florida (United States)

Solution-processed small molecule phosphorescent organic light emitting diodes (OLEDs) attract much research attention recently due to the combination of the low-cost fabrication method and decent luminance efficiencies. However, further development of such devices requires a better exciton confinement in multilayer structure, which was limited by the solvent orthogonality. Additionally, the poor stability of conventional organic HTL/HIL hindered the progress of phosphorescent OLEDs. In this study, we applied the solution-processed metal oxide as a novel HTL/HIL to replace conventional organic counterparts. In particular, the p-type nickel oxide (NiOx) and n-type electron accepting vanadium oxide (V2O5) are fully studied as HTL and HIL respectively. After spin-coating followed by appropriate treatment, a highly transparent film of either NiOx or V2O5

is formed. The oxide composition, morphology and injection/transport property of these materials were characterized by various methods. The NiOx HTL/V2O5 HIL yields an efficient device with similar or better hole transport /hole injection properties and improved stability compared to the typical organic counterparts. Our study paves the way for making efficient multilayer solution processed phosphorescent OLEDs.

8829-40, Session 6

Color tuning in organic light emitting field-effect transistors *(Invited Paper)*

Heinz von Seggern, Technische Univ. Darmstadt (Germany)

The unique property of ambipolar organic light emitting field-effect transistors (OLETs) is the ability to position the light emission zone within the transistor channel through the applied biases to the transistor terminals. In this talk the basics of the ambipolar OLET will be discussed and two examples for colour conversion will be demonstrated. Both approaches take advantage of the ability of a controlled displacement of the recombination zone through the organic semiconductors. In the first approach two different acenes with different emission colours are employed in a parallel stack in a top-contact bottom-gate FET configuration. It will be demonstrated that due to thermionic emission of electrons at the source, light of one colour can be generated near the source contact even in hole accumulation. Due to the electrically controllable positioning the charge carrier recombination zone can be directed from the top acene layer to in the bottom acene layer. Thereby the emitted light can be continuously shifted by about 50 nm from green to red. A second approach takes advantage of the horizontal displacement of the recombination zone within the channel of the transistor. On top of the semi-transparent gate electrode of a F8BT transistor a colour conversion layer is deposited in a wedge-like shape partially covering the channel. In the ambipolar regime the charge carrier recombination takes place in the F8BT layer, and dependent on the position of the recombination zone either the emitted light of the F8BT layer or the partially absorbed and converted light from the colour conversion layer can be detected. The electroluminescence maximum of the emitted light can be shifted by about 30 nm. The physics and potential applications of such colour tuneable OLETs will be discussed.

8829-41, Session 6

Low threshold polymer lasers: cavity design and fabrication *(Invited Paper)*

Ifor D. W. Samuel, Yue Wang, Emiliano R. Martins, Georgios Tsiminis, Graham A. Turnbull, Univ. of St. Andrews (United Kingdom)

The threshold is a key performance parameter of conjugated polymer lasers. Low threshold enables convenient pump sources to be used, such as nitride LEDs. We show that nanoimprint lithography can be used to make distributed feedback polymer lasers with very low thresholds, below 100 W/cm2. This process takes advantage of the favourable processing properties of polymer lasers, and has enabled us to make the first LED-pumped nanoimprinted polymer lasers. We also show how threshold can be reduced further by improved cavity design to control the relative amounts of feedback and output coupling.

8829-42, Session 6

Highly stretchable polymer light emitting devices *(Invited Paper)*

Qibing Pei, Univ. of California, Los Angeles (United States)

A fully stretchable light emitting device entails all materials employed in the device to be stretchable. Polymer composites comprised of silver nanowires or carbon nanotubes inlaid in the surface layer of a transparent polymer sheet have been developed as elastomeric transparent electrode. The surface smoothness, sheet resistance, and visual transparency of the composite electrode are comparable to ITO/glass. Depending on the polymer matrix selected, the composite electrode can be made flexible like PET or stretchable like a rubber. Polymer LEDs fabricated using the composite electrode as anode exhibit EL efficiencies higher than control devices fabricated on ITO/glass. Devices fabricated by laminating an EL polymer layer between two elastomeric composite electrodes can be elongated by greater than 40%.

8829-43, Session 6

Polymer nanofibers as novel light-emitting sources and lasing material *(Invited Paper)*

Andrea Camposeo, Luana Persano, Istituto Nazionale per la Fisica della Materia (Italy) and Istituto Italiano di Tecnologia (Italy); Dario Pisignano, Univ. del Salento (Italy) and Istituto Nazionale per la Fisica della Materia (Italy) and Istituto Italiano di Tecnologia (Italy)

Polymer micro- and nano-fibers, made of organic light-emitting materials with optical gain, show interesting lasing properties. Fibers with diameters from few tens of nm to few microns can be fabricated by electrospinning, a method based on electrostatic fields applied to a polymer solution. The morphology and emission properties of these fibers, composed of optically inert polymers embedding laser dyes, are characterized by scanning electron and fluorescence microscopy, and lasing is observed under optical pumping for fluences of the order of 10^2 J cm^-2. The reduced size of these novel laser systems, combined with the possibility of achieving wavelength tunability through transistor or other electrode-based architectures embedding non-linear molecular layers, open interesting perspectives for realizing miniaturized laser sources to integrate on-chip optical sensors and photonic circuits.

8829-44, Session 6

Recent progress on the vacuum deposition of OLEDs with feature sizes ≤ 20 ?m using a contact shadow mask patterned in-situ by laser ablation

Yoshitaka Kajiyama, Kevin A. J. Joseph, Univ. of Waterloo (Canada); Koichi Kajiyama, Syuji Kudo, V-Technology Co., Ltd. (Japan); Hany Aziz, Univ. of Waterloo (Canada)

We report progress on the development of a new technique that has the potential to enable the vacuum deposition of OLEDs with feature sizes ≤ 20um, and hence high resolution OLED displays. An OLED device with 16um by 130um sub-pixel size has been successfully demonstrated utilizing the novel idea of the in-situ shadow mask patterning method showing the capability to achieve high resolution OLED patterning. In the approach proposed here, two sheets of polyimide film are mounted on an electrode, and the top sheet of the two stacked sheets is patterned in-situ by laser ablation to create apertures. The protective under sheet is then removed, and OLED materials are deposited through the patterned slits. Since mask alignment is not required in this approach, the technique circumvents the resolution limitations imposed by the difficulty of aligning shadow masks in the conventional techniques, and allows achieving high resolution pixel patterning. Furthermore, shadow effects, another factor that limits resolution in conventional techniques, can be reduced due to the thin plastic shadow mask (~7.5um) that is directly held on the substrate by electrostatic force. In principle, by applying this technique to the standard three color side-by-side sub-pixel matrix scheme, a resolution and aperture ratio of 338ppi and 60%, respectively, can be expected, which is estimated based on the fact that the width of the deposited material is 25um for the 16um wide electrode.

8829-45, Session 7

Candle light-style OLED: a plausibly human-friendly safe night light *(Invited Paper)*

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In response to the need for a human-friendly lighting source for use at night, we demonstrate a mimic candle light organic light emitting diode (OLED) with a very high color rendering index, and an efficacy at least 300 times that of candles. The device shows an 80% lumen spectrum resemblance with the candle, which is obtained by using 4 candle light complementary emitters dispersed in two different emissive layers separated by a nano-scale carrier modulation layer. Notably, a sensationally warm candle light-style emission can hence be driven by electricity in lieu of the hydrocarbon-burning and greenhouse gas releasing candles that invented 5,000 years ago.

8829-46, Session 7

Carrier-gas enhanced vapor phase deposition for organic thin films: addressing mass manufacturing requirements for OLEDs and overcoming existing challenges with OVPD *(Invited Paper)*

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The vast majority of installed OLED manufacturing lines do utilize medium format mother glasses of Gen3.5 – Gen4.5 size (equals 650x750mm? to 730x920mm?), which are clearly too small to manufacture 56” panels and larger: a single 56” panel at 16:9 aspect ratio corresponds to approximately 1240x700mm?.

With these dimensions, cost-efficient manufacturing of OLED TV panels requires production technologies, which can handle mother glasses of Gen8 size and larger.

Using Gen8 substrates, corresponding to 2.200x2.500mm?, allow cutting 6x 55” panels or 4x 60” panels out of one mother glass sheet.

With such large area manufacturing, total cost of ownership considerations do see higher attention as for such sizes and production volumes, cost-efficiency are becoming of paramount importance.

By today, virtually all OLEDs utilizing small molecule organic stacks are deposited by vacuum thermal evaporation (VTE).

As long as scaling was not the main objective for this approach, VTE has proven to be a reliable method to make functional devices.

However, with increasing importance of total cost of ownership as well as raising technical challenges for scaling to larger areas, further propelled by the imminent need to significantly ramp-up on volumes, intrinsic limitations of VTE are understood as a challenge.

The concept of Organic Vapor Phase Deposition (OVPD®), originally developed by Stephen Forrest (*) to overcome perceived limitations of the VTE-based deposition, utilizes an inert carrier-gas for the transport of evaporated material from source to substrate and for controlling rates and composition with the partial gas flow instead of the evaporation temperature. The precise control of organic thin film processing by Organic Vapor Phase Deposition (OVPD®) is presented and analyzed on device level. With its decoupled process parameters, e.g. deposition rate, substrate temperature and deposition pressure, OVPD® offers accurate and individual control of deposition layer properties like mixing several materials (co-deposition) and the realization of various morphologies.

AIXTRON has taken the basic principle of OVPD® and, incorporating its in-house expertise of Close Coupled Showerheads (CCS®) as well as its proprietary Short Thermal Exposure Source (STExS™) technologies, offers solutions addressing the need of highly efficient production solutions for the deposition of organic thin films.

8829-47, Session 7

Hybrid white organic light-emitting diodes with high color-rendering index and stable color *(Invited Paper)*

Ma Dongge, Fangchao Zhao, Changchun Institute of Applied Chemistry (China); Hongmei Zhang, Nanjing Univ. of Posts and Telecommunications (China)

High efficiency hybrid white organic white light-emitting diodes (WOLEDs) for high color-rendering index (CRI) and stable color have been fabricated by the design of device structures. Here we fabricated two kinds of hybrid WOLEDs with red phosphorescent emissive layer/green phosphorescent emissive layer/spacer/blue fluorescent emissive layer (device 1) and red phosphorescent emissive layer/spacer/blue-green emissive layer (device 2), respectively. The key point in device 1 is using mixed 4,4?,4??-Tri(9-carbazoyl) triphenylamine (TCTA) and bis[2-(2-hydroxyphenyl)-pyridine] beryllium (Bepp2) as the host of phosphorescent EMLs as well as the spacer, which broadens the exciton distribution and improve the effective control of charge carriers in emissive layers. As a result, the hybrid WOLED exhibits a high power efficiency of 27.1 lm/W at brightness of 1000 cd/m2 and also a stable spectral emission with a high color rendering index (CRI) of 89 in a whole range of luminance. For device 2, the simultaneous emission of a blue light from the fluorescent host (Bepp2) and a green light from the phosphor (Ir(ppy)2(acac)) was realized by controlling the doping concentration of the green phosphor in the fluorescent host. It can be seen that the resulting hybrid WOLEDs achieved a CRI of 90 and kept rather stable spectral emission with Commission Internationale de L’Eclairage (CIE) coordinates of (0.42, 0.44) independent of driving voltages. This device2 also emits a high power efficiency of 23.0 lm/W at 1000 cd/m2.

8829-48, Session 7

Bending limits of flexible top-emitting OLEDs for lighting

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OLED technology has the potential to allow the fabrication of flexible light sources. Flexible OLED lighting devices have great appeal due to new design options, being unbreakable and their low weight. Metal foils are impermeable and good thermal conductors and thus promising candidates for flexible substrates. The required top-emitting architecture uses transparent thin metal electrodes. While these electrodes result in difficult optical design replacing the commonly used brittle ITO electrodes is expected to result in improved bending limits. The bending limits of such electrodes and full OLED lighting devices on metal and plastic foils were studied.

For this study samples were bent in controlled manner to varying degrees. Thereafter the samples are tested using various methods to identify operation and or encapsulation failures or electro-optical anomalies. We investigated influences from substrate material and thickness, hard coating thickness and bending type being convex or concave.

The substrate thickness is found to dominate bending limits for samples without hard coating as expected by neutral layer modeling. Hard coating shows strong improvements for all substrates increasing with thickness. Bending radii <15mm without damage to device or encapsulation are achieved. We report and discuss the main failure mechanisms as well as options for fast testing and screening of bending limits.

8829-49, Session 7

High-performance all-phosphorescent three-color white OLEDs based on a new blue phosphorescent emitter

Soichi Watanabe, Stefan Metz, Peter Murer, Heinz Wolleb, Gerhard G. Wagenblast, Christian Lennartz, Ute Heinemeyer, Ingo Münster, BASF SE (Germany)

The use of all-phosphorescent OLED lighting devices with intrinsically high quantum yields is mandatory to satisfy energy efficiency demands. However, due to the limitation of emission color and lifetime of blue phosphorescent emitters, color quality and lifetime of devices are still limited. To overcome these limitations, a new class of stable pure blue phosphorescent emitters was developed. Photophysical measurements confirm a very efficient light emission, and integration of the blue emitter together with red and green emitters into white OLED devices led to significant increase in lifetime due to electrical stabilization. Devices reported in this contribution show high correlated color temperature (CCT) of 3500-4000K, high color rendering index (CRI) 76-82, and LT50% of over 9.000 hours at 1000 cd/m2 without use of any out-coupling structure.

8829-83, Session 7

OLEDs heading towards ultra-high efficiency *(Invited Paper)*

Malte C. Gather, Technische Univ. Dresden (Germany)

We will report on recent progress in our research on high-performance organic light-emitting diodes. Particular focus is on the investigation and understanding of the micro-optic processes that influence the efficiency and emission characteristics of OLEDs. For instance, we will review our recent work on the molecular orientation of emitter molecules in OLEDs and discuss the potential of controlled emitter-molecule alignment as a way to improve device efficiency. We will also present work on a novel scattering approach that enables extraction of light that is guided inside the inner organic layers of OLEDs. It is shown that our approach is universally applicable to different device configurations, including white-emitting OLEDs.

8829-50, Session 8

Strategy for enhancing light in/out-coupling of flexible organic optoelectronic devices *(Invited Paper)*

Jong-Lam Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

Flexible electronics are pliable, thin, light-weight, impact resistant, and adaptable in design, so they have many possible applications in mobile information displays, solar cell, and general lighting. Therefore, to enable the flexible electronics, flexible substrates (plastic, steel) and fabrication methods have been studied in numerous reports. However, the required flexible nature of the substrate causes fundamental challenges. Polymeric substrates have process temperature limitations (< 350 ?) and high coefficient of thermal expansion (CTE) generating crack in devices during heating processes. A metal substrate has many advantages such as high flexibility, heat dissipation, dimensional stability and melting temperature, but the high surface roughness of the metal substrate (Ra > 100 nm) is a problem.

8829-51, Session 8

Optical design for efficient light emission in OLEDs and anisotropic layers *(Invited Paper)*

Lieven Penninck, Kristiaan Neyts, Univ. Gent (Belgium)

As organic light emitting diodes are now on the brink of large scale commercialization, detailed and reliable modeling of all emission properties of the OLED becomes essential. High efficiency, color point and angular variations should all be taken into account.

Four contributing factors to light emission in OLEDs can be identified: charge balance, singlet/triplet ratio, radiative efficiency and outcoupling efficiency. A charge balance and singlet/triplet ratio of near 100% are achieved in state of the art devices. But significant improvements are still possible in the outcoupling of light. Both radiative efficiency and outcoupling are influenced by the optical design of the organic layer stack.

Light emission is modeled as the radiation of a dipole antenna. The spectrum and angle distribution of the emission is modified by reflections from the OLED interfaces. The rigorous coupled wave analysis is used to simulate both external and internal periodic outcoupling structures. Measurements of the photo- or electroluminescent decay rate of different emitters can be used to probe the radiative efficiency and dipole orientation of the emitting molecules. We analyze and compare the importance and interaction between internal and external outcoupling structures, cathode reflectivity and oriented dipole emission.

The plane wave approach is expanded to account for anisotropic materials like liquid crystals or polymers. This approach is used to simulate emission form cholesteric liquid crystals which feature high reflectivity and low absorption due to their periodic nature. The gain threshold for lasing in cholesteric liquid crystals can be estimated by simulation and is verified experimentally.

8829-52, Session 8

Improved light outcoupling and mode analysis of top-emitting OLEDs on periodically corrugated substrates

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We demonstrate that the outcoupling of light from optimized planar top-emitting OLEDs can be further improved by exploiting Bragg scattering from periodic structures. Corrugated photoresist structures on planar glass substrates are obtained by a simple and versatile imprinting technique using a PDMS stamp carrying a sub-micron length scale grating. After UV-curing of the photoresist, the surface corrugation amounts to 39nm in depth with a period of 692nm. These samples are overgrown with a thick Al/Ag bottom contact, followed by a 345nm p-i-n OLED stack, a 20nm Ag top contact and a 70nm organic capping layer.

An optimized planar reference device with this architecture achieves an external quantum efficiency (EQE) of 11%. For devices containing the corrugated photoresist layer, the light outcoupling efficiency is increased while the electrical properties of the devices are conserved, resulting in an EQE of 12.5%.

This improvement is explained as follows: The highly reflective top and bottom contacts in our top-emitting OLEDs introduce strong microcavity effects affecting both, directly outcoupled light (i.e., the mode that is emitted into the surrounding air independent of the grating structure) and waveguided modes. Bragg scattering of waveguided modes into the forward direction can result in constructive or destructive interference with the directly outcoupled mode. In our samples, this interference results in a strong enhancement of the emission into air and in additional emission of the scattered modes in the orange-red spectral region with respect to the reference devices. Together, these effects lead to a 42% increase of the luminous efficacy.

8829-53, Session 8

Spontaneously formed nanostructure as a light extraction layer for organic light-emitting diodes *(Invited Paper)*

Jonghee Lee, Jaehyun Moon, Seung Koo Park, Chul Woong Joo, Jin-Wook Shin, Keunsoo Lee, Doo-Hee Cho, Nam Sung Cho, Joohyun Hwang, Hye Yong Chu, Jeong-Ik Lee, Electronics and Telecommunications Research Institute (Korea, Republic of)

Organic light-emitting diodes (OLEDs) have attracted considerable interest as a potential cost-efficient alternative lighting sources for both flat panel display and lighting applications and can help to solve the global energy crisis. However, there are still challenges on OLEDs, which are the out-coupling issues. The generated light in emissive layer of OLEDs is confined inside OLEDs because of refractive index mismatch between air (nair=1)/ glass substrate (nlow=1.5)/ ITO anode (nITO=2.0)/ organic (norg=1.7-1.9). Therefore, the development of efficient light extraction structures is of great necessity and significance to realize the practical applications in large area and cost-effective lighting sources.

In this paper, we report on a solution-processed wrinkled structure based film that acts a light extraction layer for OLEDs. The film can be prepared by a UV curing process of a liquid pre-polymer solution which has crosslinking moieties. After simple spin coating, the prepolymer bind to form spontaneously a wrinkled structure during the UV curing process as shown in Figure. Additionally, this film has very high haze factor over 95 and furthermore, photo-patternability thanks to the UV curable moiety.

To examine the light extraction ability, we fabricate OLEDs with the wrinkled structure as an external or an internal light extraction layer and demonstrate over 40 % efficiency enhancement because of an excellent light scattering effect.

We believe that this simple, inexpensive, and reliable system can be a key technology and will greatly contribute the development of OLEDs for both lighting and display applications.

8829-54, Session 8

A new approach to UV-blocking and passivation method for organic electronics

Illhwan Lee, Sungjun Kim, Bonhyeong Koo, Jong-Lam Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

Over the last few years, there has been much work on fabricating organic electronic devices such as organic light emitting diodes (OLEDs) and organic photovoltaics (OPVs). However, organic electronics have some limitations due to stability of organic material. In general, the exposure of organic electronic device to oxygen, moisture and Ultraviolet (UV) light leads to degradation of electrical properties. There are a number of approaches reported in the literature for protecting the organic electronic devices, which can be categorized into two groups: passivation and UV blocking.

In this work, we report that fabrication of efficient passivation and UV blocking layer by refractive index graded Distributed Bragg Reflector (DBR). DBR has high reflectivity in certain wavelength. We designed the DBR structure which can reflect at UV wavelength region (300~400 nm wavelength). The DBR is composed of silicon nitride which is well known material for passivation. Also, we can control the refractive index according to composition of Si and N ratio during silicon nitride deposition. That means the DBR structure is only composed of silicon nitride. So, we can deposit the DBR without stopping the deposition process. It is easy and fast to fabricate the UV-reflecting passivation layer.

8829-55, Session 8

Improving light extraction from large area flexible organic lighting panels

Jack W. Levell, Raghu Kishoro Pendyala, Peter A. Rensing, Alessia Senes, Stephan Harkema, Holst Ctr. (Netherlands); Olivier P. Gaudin, Solvay S.A. (Belgium); Duncan MacKerron, DuPont Teijin Films U.K. Ltd. (United Kingdom); Joanne S. Wilson, Holst Ctr. (Netherlands)

A general challenge in Organic Light Emitting Diodes (OLEDs) is to extract the light efficiently from the devices from waveguided modes within the structure. This can be accomplished by applying an additional scattering layer to the substrate which results in outcoupling increases between 25% to >100% in external quantum efficiency. In this work we aim to address this large variation in outcoupling efficiency with some general design rules and show routes to even higher performance.

Vapour deposited Organic light emitting diodes (OLEDs) have shown high efficiencies and are now commercially successful in mobile display applications. Unfortunately at the moment these devices are costly and are limited to rigid and fragile glass substrates. The high efficiency and novel form factor of OLEDs also show promise for lighting applications. In addition they offer high colour rending index and glare free and ascetically pleasing warm light without the need for bulky luminaries. However, these devices show additional promise if used with flexible shatterproof substrates while facilitating low cost manufacture. Holst Centre and partners are developing flexible substrates and roll to roll compatible processing techniques to enable this next step in OLED development both for lighting and display applications.

In this work also show that refining the light extraction using specially designed flexible PEN substrate foils with DuPont Teijin Film we have enhanced performance in partially solution processed 69 cm2 OLEDs with scattering from 30 lm/W to 42 lm/W at 1,000 cd/m2 luminance with Solvay and Plextronics.

8829-56, Session 8

Enhanced light out-coupling from surface plasmonic loss minimized transparent organic light-emitting diodes

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Light extraction of organic light emitting diodes (OLEDs) has been an important issue in order to increase the external quantum efficiency (EQE) of the devices for displays and solid-state lighting, because 70%~80% of the emitted light is confined in the substrate (substrate mode), in the organic layer and in the transparent electrode (waveguide mode), or lost by absorption and surface plasmon polaritons of the metal electrode (absorption and SPP mode). Various methods have been proposed to extract the substrate mode and/or the waveguide modes. However, the absorption and SPP losses by the metal electrode(s) in bottom and top emission OLEDs cannot be avoided in most cases, therefore we need to minimize them in OLEDs to increase the EQE.

Several approaches have been suggested to reduce the surface plasmon loss, such as by controlling the molecular orientation of the emitter, increasing the distance between the emitting layer and the metal electrode, or fabricating a metal electrode free OLED. A metal free OLED with good transparency combined with a method to extract the light efficiently from the device could be a solution for the purpose of reducing the surface plasmon loss.

In this presentation, we will demonstrate through simulation that the surface plasmon and intrinsic absorption loss in OLEDs can be significantly reduced by using a metal free transparent OLED based on TCO electrodes, in contrast to other OLEDs with metal electrodes, maximizing the total amount of extractable light. By integrating microstructures on both sides of a transparent OLED to extract the confined light, we have experimentally realized an OLED with an EQE

value of 47.3%, enhanced from 18.2% without the microstructures. The efficiency was enhanced further to 62.9% by integrating a micro-cone array on one side and a half-sphere lens on the other side. The experimental results are well described by a combined simulation of the classical dipole model and the 3 dimensional ray tracing method. Moreover, the transparent OLED with the microstructures showed no color shift with viewing angle. A simple process which combined the high efficiency and no color shift suggests the great potential of our device for application in solid state lighting.

8829-57, Session PWed

Direct measurement of the composition profile in graded emissive layer organic light-emitting devices and its relation to device performance

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In this work, the composition profile of graded emissive layer (G-EML) organic light-emitting devices (OLEDs) is examined through the use of X-ray photoelectron spectroscopy (XPS) with a gas-cluster ion-beam (GCIB) milling tool. The use of Argon in the GCIB allows for careful control of the sputtering rate of the organic layers and avoids altering or contaminating the chemical environment of the exposed organic surfaces. Together, the GCIB and XPS allow precise identification of the chemical state, and quantity, of molecular species as a function of depth through the organic active layers. This technique is applied to devices containing a continuously-varying host composition from predominately hole-transporting material (HTM) at the anode to predominately electron transporting material (ETM) at the cathode. Devices having overall composition profiles of 2:1, 1:1, and 1:2 HTM:ETM show distinct operation and performance differences. These differences are attributed to a variation in the composition of the HTM and ETM materials throughout the device, confirming that the as-deposited composition profiles are distinct, are present post-processing, and are responsible for the changes in operation observed. G-EML based OLEDs have shown promise in achieving highly efficient operation while being fabricated in a single deposition step, potentially allowing for the realization of simple, efficient OLEDs.

8829-58, Session PWed

Efficient near-infrared emission at 1.3 micron range of narrow-band phthalocyanines thin-films

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Organic near-infrared (NIR) emitting materials are extremely rare and receive increasing attention. The optical properties of organic compounds are determined by their energy band gap. Considering several design factors for tuning the energy band gap, we have designed and synthesized a new aza metal-free phthalocyanine containing four 1,10-phenanthroline subunits. The maximum absorption wavelength reaches beyond 1 micron for the aggregated solid samples. The solution deposited thin-film shows fluorescence emission lies in the blue region with a maximum at 460 nm and also emission lies in the NIR region with a maximum at 1292nm. Such a NIR emission at 1.3 micron range, i.e., zero dispersion wavelengths of fiber, is extremely rare for organic compound. The great red shift in optical activity, in our view, lie in at least two aspects: the molecular structure as well as the aggregation formed by molecular interactions. The extension of the conjugation leads to a reduction of the gap between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO). Adding of the peripheral electrophilic subunits also reduce the LUMO energy level. On the other hand, the aggregated state effect not only broadens the emission spectrum, but also causes the great red shift of the fluorescence emission. The energy band gap is determined to be 1.1eV by the cyclic voltammetry measurement which further explains the NIR optical activity. This paper provides a new thought and experimental data for developing organic NIR materials.

8829-59, Session PWed

Optimization of stacked inverted top-emitting green electrophosphorescent organic light-emitting diodes

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Different green electrophosphorescent two-unit stacked organic light-emitting diodes (OLEDs) with inverted top-emitting structures are demonstrated. These devices combine the advantages of inverted top-emitting OLEDs with the benefits gained from having a stacked architecture. The electrical and optical characteristics of the two-unit stacked OLED are evaluated by comparing their performance to that of the constituent single-unit OLEDs. The connecting-unit between the two light-emitting units consists of Al/LiF/1,4,5,8,9,11-hexaazatriphenylene hexacarbonitrile (HAT-CN). The performance of the stacked OLED is shown to be highly sensitive to the thicknesses of the thin layers of Al and LiF, as well as the choice of the hole transport-material in the hole-transport layer adjacent to the connecting-unit. Device performance increases when the Al interlayer thickness is increased from 1.0 nm to 2.5 nm. This could be due to the increased conductivity of the connecting unit with thicker Al, improving electron injection into the neighboring light-emitting unit. Decreasing the LiF thickness from 2.5 nm to 1.0 nm also results in a significant enhancement in device performance. The poorer performance of the stacked OLED with 2.5 nm of LiF could be due to the connecting-unit becoming too insulating at this greater LiF thickness. Finally, when the hole transport material adjacent to the connecting-unit is changed from N,N'-Di-[(1-naphthyl)-N,N'-diphenyl]-(1,1'-biphenyl)-4,4'-diamine (?-NPD) to 1,1-bis-(4-bis(4-methyl-phenyl)-amino-phenyl)-cyclohexane (TAPC), the device performance is significantly improved. With a TAPC hole-transport layer, the two-unit stacked OLED has a current efficacy of about twice that of a single-unit OLED. A final optimized device with an (?-NPD) optical outcoupling layer achieves a current efficacy exceeding 200 cd/A at luminance values up to 1,000 cd/m2.

8829-60, Session PWed

Highly efficient red-emitting OLEDs based on a novel phosphorescent iridium(III) complex

Bona Yang, Hye Jin Lee, Sung Nam Lee, Dongmyung Shin, Hongik Univ. (Korea, Republic of)

A new phosphorescent Iridium complex, Ir(TMP-TT)2(acac) was synthesized for organic light-emitting diodes (OLEDs). This material was designed by result of Gaussian modeling program. The ligand, TMP-TT, have sites of both the electron donor and acceptor in structure. So, It showed Intramolecular Charge Transfer(ICT) property. The TMP-TT was synthesized by Suzuki coupling reaction, and Ir(TMP-TT)2(acac) was synthesized by Nonoyama reaction. The UV-Visible absorption peak of TMP-DT was measured to be at 363 nm and its photoluminescence (PL) emission spectrum showed blue light-emission peaked at 425 nm in chloroform solvent. The devices fabricated by Ir(TMP-TT)2(acac) as emitting layer dopant. The device structures were ITO / NPB / CBP: Ir(TMP-TT)2(acac) / Bphen / Liq / Al.

8829-61, Session PWed

New platinum complexes for hybrid white organic light-emitting diodes

Anurach Poloek, Chin-Ti Chen, Academia Sinica (Taiwan); Chao-Tsen Chen, National Taiwan Univ. (Taiwan)

Two groups of platinum(II) complexes containing hydroxynapthyridine derivatives or octaphenyltatraazaporphyrin ligands were newly synthesized, and their photophysical properties were examined. Single crystal X-ray diffraction of some of the platinum(II) complexes were determined to elucidate their variation of solid state phosphorescence and electroluminescence. Organic hole transporting as well as blue light-emitting NPB (1-naphthylphenylbiphenyl diamine) or 4P-NPD (1-naphthylphenylquaterphenyl diamine) was employed in the platinum complex-based hybrid white organic light emitting diodes (WOLEDs) with a simplified device configuration of ITO/4P-NPD/CBP:platinum complex/TPBI/LiF/Al or ITO/4P-NPD/4P-NPD: platinum complex /TPBI/LiF/Al.

8829-62, Session PWed

Al2O3/TiO2 multilayer thin film encapsulation for top emitting OLED using ALD process

Lae Ho Kim, Seonuk Park, Chan Eon Park, Pohang Univ. of Science and Technology (Korea, Republic of)

Organic light-emitting diodes (OLED) have great potential for use in next-generation flat-panel display due to their many advantages, such as their fast response, light weight, wider viewing angles and for use with flexible displays. It is still remain to solve the problem of low light-out coupling efficiency and short lifespan. One of the method to overcome low light extraction efficiency is that control the microcavity structre in OLEDs. We were fabricated top emitting OLED and then deposited stacks of Al2O3 and TiO2 layer for encapsulation using atomic layer deposition (ALD) process. The properties including electrical characteristics (I-V-L), EL spectra, and water vapor transmission rate were investigated.

8829-63, Session PWed

Triplet-triplet annihilation in phosphorescent organic light emitting diodes

Yifan Zhang, Stephen R. Forrest, Univ. of Michigan (United States)

Triplet-triplet annihilation (TTA) has been identified as a significant source for efficiency roll-off at high brightness (> 1000 cd/m2) in phosphorescent organic light emitting diodes (PHOLEDs). TTA can be described as the collision between two triplets resulting in de-excitation of one of them. To fully understand TTA, we developed a dynamical model that includes both triplet diffusion and triplet-triplet energy transfer. From the transient photoluminescence of a variety of widely used iridium and platinum complex doped films, we extract the TTA rates. By comparing these rates to model predictions, we find the triplet diffusion dominates TTA. Further, the TTA rate dependence on phosphor doping concentration suggests triplet diffusion follows a Dexter type exchange interaction. Interestingly, iridium complexes have approximately two orders of magnitude higher radiative decay and TTA rate than platinum complexes. To maintain the PHOLED efficiency at high brightness, the TTA rate must be minimized, while maximizing the radiative decay rate. These two rates are independent in the case of Dexter transfer. Thus, we find the difference in TTA rates between the Ir and Pt complexes can be explained by the coincidence in energy between the excited and ground states of the respective molecular species. Thus, minimizing the emission and absorption spectral overlap is a useful means for selecting phosphors for high efficiency PHOLEDs operating at high brightness.

8829-64, Session PWed

Synthesis of fluorene-based polyelectrolytes tethering different counterions for single-component white light-emitting electrochemical cells

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We demonstrate the synthesis and characterization of fluorine-based polyelectrolytes tethering Br, BF4, or PF6 counterions. 2,1,3-Benzoselenadiazole moieties were incorporated into polymer main chains to produce single-component white light-emitting polymers. The thermal stability of Br-containing ionic polyfluorenes was decreased because of the Hofmann elimination occurred at higher temperature. By replacing Br with BF4 or PF6 counterions, the thermal stability of polymers was significantly improved. UV-vis absorption and photoluminescence spectra revealed that Br-containing ionic PF generates blue shift in methanol, while BF4 and PF6-containing ionic PFs show blue shift in acetonitrile. Electrochemical analysis revealed that oxidation potentials of BF4 and PF6-containing ionic PFs were decreased, resulting in increase in HOMO and LUMO levels. The white light-emitting electrochemical cells (WLECs) with the configuration of ITO/PEDOT/polymer/Ag showed a maximum luminescence efficiency of 1.56 lm/W at a low operation bias of 3 V. The single-component LEC device exhibited pure white light emission with CIE'1931 coordinates approaching (0.33, 0.33) and high color rendering index (CRI > 85), referring to its potential use in solid-state-lighting application.

8829-65, Session PWed

The far-field optical distribution profiles and properties of a planar white organic light-emitting diode

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The far-field optical distribution profiles and characteristics of a planar white organic light-emitting diode (WOLED) with 10x10mm2 emitting area were experimentally investigated by using a 2-axis automatic optical measuring system in which the optical power distribution can be measured in hemi-spherical space. The far-field optical distribution profiles and characteristics of a lighting source are crucial for practically designing specific lighting application. WOLED has become a potential planar lighting source due to its single device structure consisted of multiple organic layers sandwiched by cathode and anode electrodes on glass substrate. This relatively large planar device can be regarded as one of the most unique features compared to a point-source white LED (WLED). The far-field optical distribution characteristics of a WOLED planar lighting source is also expected to be unique and different compared to that of a point source. Our preliminary experimental result measured from a point-source WLED indicates that its far-field optical distribution profile is close to the ideal point-source. Our experimental result measured from a WOLED with 10x10mm2 emitting area reveals its far-field optical distribution characteristic is slightly different from a point source.

8829-66, Session PWed

Improvement of operation voltage and efficiency in inverted blue phosphorescent organic light-emitting devices

Chih-Hao Chang, Hao Siang Huang, Yu-De Su, Chuan-Hao Chiu, I-Chun Lien, Yi-Hu Liang, Yu-Shuo Chang, Yuan Ze Univ. (Taiwan); Hsin-Hua Chang, Vanung Univ. (Taiwan)

An increasing number of smart phones, digital cameras, and tablet PCs use active-matrix OLED (AMOLED) for displays, taking advantage of the performance improvements over passive-matrix OLEDs. Inverted OLEDs (IOLEDs) have drawn considerable attention for use in AMOLED displays because of their easy integration with n-channel metal-oxide based thin film transistors (TFTs). In general, an IOLED consists of a top anode and a bottom cathode that connects to the drain end of the TFTs. To meet the stringent requirement of the TFTs, it is highly desirable to decrease the operation voltage of the IOLED. In this study, we focus on the developing blue phosphorescent, bottom-emission IOLEDs with low operating voltages through the use of adequate-charge injection materials. The most crucial issue for IOLEDs is the poor electron injection caused by the bottom cathode. According to previous reports, the turn-on voltages of FIrpic-based IOLEDs are within a range from 4 to 8 V. This study successfully demonstrates a turn-on voltage as low as 3.5 V for bottom-emission IOLEDs. The electron injection layers were constructed by combining an ultrathin aluminum layer with an alkali metal oxide layer. The peak efficiencies of the IOLEDs reached 15.8%, 32.5 cd/A and 27.7 lm/W. Furthermore, the light extraction technique could be used to improve device performance. Thus, an embedded nanocomposite film is integrated into the IOLEDs to further improve the operating voltage and efficiency.

8829-67, Session PWed

Recent progress on solution processable small molecules for organic light-emitting diodes in ITRI

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A series of novel phosphorescent dopants containing thieno[3,2-c] pyridine-based ligand were synthesized and characterized. By introducing electron withdrawing/donating substituents, the emission wavelength of these Ir complexes can be tuned from blue to red region. The conventioal vacuum-deposted devices exhibited high efficiencies. The yellow devices showed extremely high efficiency of 98 lm/W@1000 cd/m2. The green devices with efficacies of 56 cd/A and 39 lm/W were reported with the brightness of 1447 nits. When double emitting layers were adopted, the efficacy was improved to 63 cd/A and 44 lm/W@1257 nits. Recently, solution-processed small-molecule OLEDs have drawn many intentions and shown continuously improving efficiency. We successfully fabricated RGBY OLEDs by solution/evaporation hybrid process. The performance of green solution processed OLEDs without HTL showed relatively high efficiency of 36 cd/A and 28 lm/W@1240 cd/m2.

8829-68, Session PWed

Improved light extraction of white LED using the CdSe/ZnS QDs embedded in blue polymer matrix by efficient energy transfer

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We propose white-light emitting diode (WLED) that is made up of colloidal QDs embedded in polymer matrix as a hybrid single emissive layer. The red/green colored QDs were mixed with blue emissive PFO to form hybrid emissive layer and it generated proper white emitting with basic structure of OLED. The WLED consist of ITO, PEDOT:PSS, poly-TPD blended with PVK for reducing the hole injection barrier, emissive layer, Alq3, and LiF:Al. As a result, our WLED showed brightness of 1,163 cd/m2 and 1.01 cd/A of efficiency at (0.33, 0.36) CIE coordinate. Inspection of these results, we optimized WLED structure for charge balance in emissive layer and enhanced color purity for the white emission.

8829-69, Session PWed

White light emission from alternating current organic light-emitting devices using high frequency color-mixing

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We report on a novel device concept for organic light-emitting devices (OLEDs) which requires no charge injection from external electrodes and instead uses a capacitively-coupled alternating current (AC) driving signal to operate the device. Here, we show for the first time the generation of white light from these AC-OLEDs. In our approach, both half-cycles of a sinusoidal driving signal are used to independently address a phosphorescent green as well as a triplet-harvesting blue/red unit. Both emission units are spatially separated and connected by sharing a common n-doped electron transport layer. Upon application of a sinusoidal driving voltage, the device alternately emits green and purple light. For high frequencies, the human eye cannot resolve this modulation and the emitted light is perceived as white. This approach yields devices with warm-white color coordinates (0.43, 0.44) and a CRI of 77 at high brightness values of up to 1000 cd/m?. Modifying the AC driving scheme in terms of pulse-height and/or pulse-width of both positive and negative half-cycle can be used to address both emission units separately, providing control over the composition/color-point of the emitted light.

We show evidence proving that the devices operate on a capacitive-coupling based driving scheme and that the emission is solely due to charge carriers provided by the doped transport layers. High dielectric constant insulating layers between electrodes and organic layers efficiently suppress charge carrier injection and improve the Zener tunneling mechanism that is required to replenish the depleted transport layers after each emission cycle.

8829-70, Session PWed

Organic/electrode interfacial photo-degradation in organic optoelectronic devices

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Electrical contacts are integral components of nearly all organic optoelectronic devices such as organic light emitting devices (OLEDs) and organic photodetectors (OPDs), creating organic/electrode interfaces. Indium tin oxide (ITO) and metals are frequently used as electrode materials in these devices. Due to their critical role in device performance, organic/electrode contacts have been the focus of numerous investigations, aiming at studying the chemical and electronic properties of these interfaces. Surprisingly, and despite the high illumination intensities that these interfaces are subjected to in optoelectronic devices, the effect of irradiation on these interfaces and their photo-stability have not been studied until very recently.

We recently discovered that both ITO/organic and organic/metal interfaces are susceptible to irradiation. This photodegradation leads to deterioration in both charge injection and extraction. In this work we present results from investigations on various organic/electrode contacts, and employ fluorescence lifetime measurements to verify that the photo-induced changes occur mainly at organic/electrode interfaces rather than in bulk organic layers. Such organic/electrode interfacial photo-degradation is found to play an important role in the degradation of OLEDs and OPDs, where the interfacial photo-degradation is caused by either device own electroluminescence or external irradiation.

Furthermore, approaches for reducing organic/electrode interfacial photo-degradation are studied. For the ITO/organic interface, the use of MoO3 interfacial layer and CF4/O2 plasma treatment is found to significantly improve the interfacial photo-stability. For the organic/metal interface, on the other hand, the use of interfacial layers such as Cs2CO3, LiF and Li-acetylacetonate of an optimum thickness is found to be effective.

8829-71, Session PWed

Effect of Thermal Annealing on Electroluminescent Properties of Undoped and Doped Polyfluorene OLEDs

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The effect of thermal annealing on electroluminescence properties of polyfluorene-based organic light emitting diodes (OLEDs) was studied. Two types of light emitting layers were investigated: undoped layers made of poly(9,9-di-n-octylfluorenyl-2,7-diyl) (PFO) and doped layers consisting of 95 wt-% of PFO and 5 wt-% of poly[(9,9-di-n-octylfluorenyl-2,7-diyl)-alt-(benzo[2,1,3]thiadiazol-4,8-diyl)] (F8BT). Light emitting layers were spin coated from o-xylene solutions on top of glass substrates preliminary covered with ITO and PEDOT:PSS films. Prior to vacuum deposition of LiF/Al top contacts, the thermal annealing treatment was performed in the oven at 190 ºC or 290 ºC. All the fabrication steps and characterization procedures were executed in the nitrogen-filled glove boxes, excluding spin coating of water-based PEDOT-PSS.

The experiments indicated that the annealing treatment results in significant changes of luminescence and current efficiency in both types of the considered OLEDs, however, the annealing temperature affects them differently. For the undoped OLEDs the current efficiency was highest for the devices annealed at 190 ºC. For the doped OLEDs the highest current efficiency was observed in non-annealed devices. Remarkably, green emission originating from F8BT was observed for the doped OLEDs in the case of non-annealed and annealed (290 ºC) devices. Whereas, the spectrum of the similar devices annealed at 190 ºC had an additional strong blue component corresponding to PFO emission. This fact can be explained by a phase separation between the dopant and host polymers appearing at 190 ºC and leading to incomplete Förster energy transfer from the host to dopant polymer.

8829-72, Session PWed

Efficient blue emitters based on linear carbazole-fluorene triads

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Realization of efficient blue emitters, particularly, electrically-pumped organic semiconductor laser still remains a challenge. Recently, linear multi-fragment molecular structures based on carbazole or fluorene functional units and featuring extended pi-conjugation attracted attention as promising blue-emitters with emitting dipoles oriented in the plane of the active layer [1,2].

In this work, emission efficiency, excited state lifetime, fluorescence concentration quenching and amplified spontaneous emission of a series of linear carbazole-fluorene triads, designed for lasing applications, were investigated. The triads expressed high fluorescence quantum efficiency in both dilute solutions (~90 %) and neat solid films (up to 60 %), short excited state lifetimes (0.7-1.2 ns), what resulted in high radiative decay rates beneficial for achieving low threshold of amplified spontaneous emission (ASE). Additionally, the linear triads exhibited negligible concentration quenching up to 10 wt % when dispersed in rigid polymer matrix while maintaining high fluorescence quantum efficiency (70-80%). These features enabled to achieve ASE for the compounds dispersed in the polymer matrix in a wide concentration range (0.5 – 10 wt %) with the threshold of as low as 10 kW/cm^2. Based on the density functional theory calculation results and the experimental data the influence of intramolecular twisting, type and the linking topology of the fragments on the emission properties and ASE threshold are discussed.

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8829-73, Session PWed

OLED emission zone measurement with high accuracy

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The spatial distribution of the light generation rate in Organic LEDs (OLED), often referred to as the ‘emission zone’, is subject to continuous investigation for many reasons. First, its simulation [1] is desired in order to achieve design based engineering of OLED stacks. Second, its knowledge is required to estimate the internal electro-optical conversion efficiency from far-field measurements. Furthermore, complicated processes such as device ageing might affect the emission zone as well, thus suggesting an approach to gain insight into the underlying phenomena.

The experimental analysis of the emission zone in electrically operated OLEDs usually rely on reverse simulation of radiation pattern measurements [2,3,4], and superior resolution has been claimed for extended polymer emitters [2]. Although this approach seems to be straight-forward, the radiation pattern usually consists of a convolution of multiple emitter properties, and adapted OLED stacks and analytical procedures need to be utilized [5].

In the case of highly efficient state of the art devices, the thickness of emitting layers is in the order of 10 nm. We discuss the problem of emission zone measurement mathematically for such systems, utilizing singular value decomposition (SVD) of the linear problem. This yields insight into the potentially achievable spatial resolution, and allows one to verify experimental approaches (e.g. to use half-ball lenses to access internal substrate patterns). Experimental results illustrate the theoretical results and prove the validity of the approach.

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8829-75, Session PWed

Semitransparent Ag/HAT-CN anode structure in high-performance inverted top-emitting organic light-emitting diodes

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Inverted top-emitting green electrophosphorescent organic light-emitting diodes (OLEDs) with a Ag/1,4,5,8,9,11-hexaazatriphenylene hexacarbonitrile (HAT-CN) semitransparent anode structure are demonstrated. The devices are fabricated upon polyethylene dioxythiophene-polystyrene sulfonate (PEDOT:PSS)-coated glass substrates. The cathode consists of Al and an electron-injection layer of lithium fluoride (LiF). The OLEDs contain an electron-transport layer of 1,3,5-tri(p-pyrid-3-yl-phenyl)benzene (TpPyPB) and an emissive layer comprising tris(2-phenylpyridine)iridium(III) (Ir(ppy)3) doped in a 4,4’-bis(N-carbazolyl)-1,1’-biphenyl (CBP) host (doped at 6% by volume). Two different device structures are compared, differing only in the choice of material for their hole-transport layers (HTLs). The HTL is composed of either CBP or 1,1-bis-(4-bis(4-tolyl)-aminophenyl)cyclohexene (TAPC). The devices with an HTL of TAPC show superior performance to those with an HTL of CBP. To clarify the alignment of the energy levels of these materials, the material interfaces must further investigated by inverse photo electron spectroscopy and ultraviolet photoelectron spectroscopy. Additionally, devices were fabricated with different thicknesses of HAT-CN and an HTL of TAPC. Devices with 1 nm, 5 nm, and 15 nm of HAT-CN show very similar performance indicating insensitivity to the HAT-CN thickness and demonstrate that as little as 1 nm of HAT-CN is sufficient

for efficient interfacial charge transfer. Devices with 0 nm showed no light emission. Optimized devices with an N,N'-Di-[(1-naphthyl)-N,N'-diphenyl]-(1,1'-biphenyl)-4,4'-diamine (?-NPD) optical outcoupling layer on the semitransparent anode have a low turn-on voltage of 3.0 V and a current efficacy of 118.9 cd/A at a luminance of 115.8 cd/m2. This current efficacy stays above 100 cd/A for luminance values up to 6,000 cd/m2.

8829-76, Session PWed

Doping-concentration-dependent hole mobility in p-doped amorphous organic semiconductors

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Despite decades of research on electrical doping and its utilization in organic electronics, our fundamental understanding of the doping effect in organic semiconductors is still far from complete, compared to the case of inorganic semiconductors. One example is the effect of doping on charge-carrier mobility, where different systems display different behaviors. The hole mobility was increased with increasing doping concentration in F4-TCNQ doped m-MTDATA, MoO3-doped NPB, F4-TCNQ-doped MEH-PPV, and F4-TCNQ-doped ZnPc. Hole mobilities were measured using field-effect transistors (FETs) or space-charge-limited current (SCLC). On the other hand, other studies report that the hole mobility is reduced by increasing the doping concentration in F4-TCNQ-doped P3HT, and F4-TCNQ-doped ?-NPD. We believe one of the main reasons for these different behaviors is related to the dependence of the carrier mobility on the carrier density in the amorphous organic semiconductors. When the mobility is measured using FETs and SCLC measurements where the injected carrier density is greater than the free-carrier density generated by doping, the total carrier density in the organic semiconductors is dominated by the carriers injected via the electrodes.

In this presentation, we report the effect of electrical doping on the hole carrier mobility in a p?doped organic semiconductor in the ohmic current region where the density of carriers generated by doping is much higher than that of injected carriers to exclude the effect of the injected charge-carrier density and the electric field. The hole mobility decreases as the doping concentration increases, indicating that the negatively charged dopants form Coulomb traps that disturb hole transport in the p?doped organic system. The activation energy of the mobility increases as the doping concentration increases, consistent with a broadening of the Gaussian density-of-states distribution.

8829-77, Session PWed

High-throughput quantum chemistry and virtual screening for OLED material components

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Computational structure enumeration, analysis using an automated simulation workflow and filtering of large chemical structure libraries to identify lead systems has become a central paradigm in drug discovery research. Transferring this paradigm to challenges in materials science is now possible due to advances in the speed of computational resources and the efficiency and stability of chemical simulation packages. State-of-the-art software tools that have been developed for drug discovery can be applied to efficiently explore the chemical design space to identify solutions for problems such as organic light-emitting diode (OLED) material components. In this presentation, virtual screening for OLED ETL and HTL layer materials based on intrinsic quantum mechanical properties is illustrated. Also, a new approach to more reliably identify candidate systems is introduced that is based on the chemical reaction energetics of decomposition pathways for OLED materials.

8829-78, Session PWed

Low roll-off and high efficiency orange OLEDs using green and red dopants in an exciplex forming co-host

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Orange emitting organic light emitting diodes (OLEDs) are important in order to achieve highly efficient hybrid tandem white OLEDs, in which a blue fluorescent (FL) and an orange phosphorescent emitting system are connected by using a charge generation unit. These hybrid tandem white OLEDs take advantage of a stable blue fluorescent unit with a long device lifetime and a high efficiency orange phosphorescent unit, and are the most widely used structure for displays and solid state lighting.

There are two possible ways to construct an orange phosphorescent OLED. One way is to utilize a single orange emitting phosphorescent material. The other way is to utilize both green and red emitting phosphorescent materials. The first method has the advantages of easy fabrication and color stability with increasing luminance over the second method. However, it is difficult to synthesize an orange emitting phosphorescent dye covering both the green and red regions of the spectrum, resulting in a low color rendering index (CRI) and a low color gamut (CG) when combined with a blue emission in white OLEDs.

The combination of green and red emissions leads to an orange emission with a broad spectrum. Moreover emitting color can be tuned from green to red by adjusting their doping ratio. This quasi orange emitter results in white OLEDs with high CRI values compared to white OLEDs with just one type of orange emitting molecule when combined with a blue emitting layer.

Large numbers of tandem white OLEDs incorporating orange OLEDs have been reported using green and red phosphorescent dyes. Unfortunately, however, there are only a limited number of papers on the orange OLEDs themselves and their EQE values were less than 17.6% to our best knowledge.

In this presentation, we demonstrate high efficiency orange emitting OLEDs with low driving voltage and low roll-off of efficiency using an exciplex forming co-host by (1) co-doping of green and red emitting phosphorescence dyes in the host and (2) red and green phosphorescent dyes doped in the host as separate red and green emitting layers. The former orange OLEDs achieved a low turn-on voltage of 2.4 V, which is equivalent to the triplet energy gap of the phosphorescent-green emitting dopant, and a high external quantum efficiency (EQE) of 25.0%. Moreover, the OLEDs showed low roll-off of efficiency with an EQE of over 21% at 10,000 cdm-2. The device displayed a very good orange color (CIE of (0.501, 0.478) at 1,000 cdm-2) with very little color shift with increasing luminance. The transient electroluminescence of the OLEDs indicated that both energy transfer and direct charge trapping took place in the devices. The latter OLED shows the maximum external quantum efficiency (EQE) of 22.8%, low efficiency roll-off with the EQE of 19.6% at 10,000 cd/m2, and good orange color with the CIE coordinate of (0.442, 0.529) and no color change from 1,000 to 10,000 cd/m2. The exciplex forming co-host system distributes the recombination zone all over the EMLs and reduces the triplet exciton quenching processes.

8829-79, Session PWed

ITO-free top emitting high efficiency organic light emitting diodes

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The field of organic electronics and specifically organic light emitting diodes (OLEDs) have significantly advanced in the last decade driven by the promise of light weight, flexible, extremely thin, high colour contrast, and high efficiency displays and lighting. However, increasing the out-coupling efficiency of emitted light is still a challenge. Conventionally, OLEDs have a bottom emitting structure with Indium Tin oxide (ITO) as the transparent anode, and in such a structure ~ 80 % of the generated light is lost in waveguided modes, and hence only ~ 20 % is out-coupled. Therefore, increasing the out-coupling of emitted light is an important goal for OLEDs. Here we present an ITO-free high efficiency fluorescent emitter-based OLED using a top emitting structure. A multilayer electrode comprising of MoOx(5nm)/Ag (10 nm)/MoOx (40 nm) MAMs) was used as an anode while fluorescent polymer Super Yellow (SY) was used as the emissive layer. The device has a structure: substrate/Al/Cs2CO3/SY/MAMs. For comparison, bottom emitting 'standard' ITO devices with structure: substrate/ITO/PEDOT:PSS/SY/Ba/Al were also fabricated. Current efficiency and external quantum efficiency of top emitting MAMs devices were found to be double that of the standard ITO devices, reaching a maximum of 21.2 cd/A and 6.69 %, respectively. These efficiencies are better than those reported MAMs-based OLEDs with phosphorescent materials in which the MAMs were used on the cathodic side of the device. The enhancement in efficiency is directly attributable to the increased out-coupling of light in the top-emitting configuration where light loss in substrate mode is suppressed. Out-coupling efficiency of the top emitting MAMs devices was estimated to be ~ 40%.

8829-81, Session PWed

Correlation between shift in recombination zone and efficiency roll-off in phosphorescent organic light emitting devices (PHOLEDs)

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We studied the correlation between shift in recombination zone and efficiency roll-off in typical PHOLED based on the archetypical 4,4'-bis(carbazol-9-yl)biphenyl (CBP) and Tris(2-phenylpyridine)iridium(III) [Ir(ppy)3] host-guest system. To probe the shift in recombination zone, electroluminescence (EL) spectra of devices with various architectures at different current densities are studied. Results show that increase of current density shifts the recombination zone from the emission layer (EML)/electron transport layer (ETL) interface toward the hole transport layer (HTL)/EML interface. Results from the delayed electroluminescence intensity suggest that Host-Host Triplet-Triplet Annihilation (TTA) mostly occurs at the region close to the EML/ETL interface implying a presence of large number of host excitons. On the other hand, Host-Host TTA is insignificant at the HTL/EML interface implying a reduction of host excitons at the vicinity of this interface. The Results further imply that the luminance at low current density mostly originates from the e-h recombination on the host followed by energy transfer to the guest and at high current density direct e-h recombination on the guest is the main emission mechanism. The results suggest that the shift in recombination zone and subsequent change in emission mechanism plays a major role on the efficiency roll-off.

8829-82, Session PWed

Hexaazatriphenylene-Hexanitrile (HATCN) as an anode buffer layer for high performance transparent inverted OLEDs

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We employed 1,4,5,8,9,11-hexaazatriphenylenehexacarbonitrile (HATCN) as an anodic buffer layer between the active layer and the indium zinc oxide (IZO) top electrode and demonstrated a high performance inverted transparent OLED. HATCN, a discoid organic molecule possessing a deep lowest unoccupied molecular orbital (LUMO) level, good hole injection characteristics, low refractive index of about 1.7 in the visible wavelength and very high stability even in ambient air conditions, is thermally evaporated at low temperature below 300oC in vacuum. The device showed a total maximum luminance and a power efficiency of 67 cd/A and 67 lm/W, respectively, when the emitted lights through both the bottom and top sides are summed, and this is almost double the efficiency compared to the best values reported up to now in transparent OLEDs, to the best of our knowledge. The experimental data showed excellent agreement with the optical simulation results based on the classical electromagnetic theory with a full vectorial approach. The fact indicates that HATCN not only perfectly protects the organic active layers from sputtering bombardment, but also acts as a good hole injection layer even after sputter bombardment. Based on the x-ray and atomic force microscopy measurements, it was confirmed that the molecular alignment and nanostructure of HATCN thin films stacked with a (00l) hex preferred orientation on organic surfaces and the orientation was maintained even after deposition of the IZO electrode. Moreover, the inverted OLEDs showed the best transmittance reported up to now with an average transmittance of 81% in the visible spectrum range.

8830-1, Session 1

Design and synthesis of small molecules for the fabrication of high efficiency solar cells *(Keynote Presentation)*

Guillermo C. Bazan, Univ. of California, Santa Barbara (United States)

High charge separation efficiency combined with the reduced fabrication costs associated with solution processing and the potential for implementation on flexible substrates make "plastic" solar cells a compelling option for the next generation of photovoltaic devices. The control the donor/acceptor blend morphology in bulk heterojunction materials as required for achieving high power conversion efficiency is therefore of primary concern. We showed that by incorporating a few volume percent of high boiling point solvent additive, the power conversion efficiency of photovoltaic cells (AM 1.5 conditions) is substantially increased, and this method of optimization is now the most widely used processing option for polymeric systems.

Previous examination of the active layers has shown that the additives influence the size of the domains within the bulk heterojunction (BHJ) organization and can improve the order within the polymer domains. In the first part of this presentation, we disclose in-situ grazing incidence wide-angle x-ray scattering as a function of time to explore the dynamics of the BHJ evolution. These studies show that a small percentage of octanedithiol in chlorobenzene induces the nucleation of polymeric crystallites within two minutes of deposition, increases the orientational order of specific polymorphs, and allows further crystallite nucleation over a period longer than 40 minutes after casting. These observations are absent when the same BHJ blend is cast from pure chlorobenzene.

In the second part, we will examine a new class of small molecules with modular features that can be used to fine tune the optical absorption to match the solar spectrum, molecular orbital energies that are appropriate to achieve excellent power conversion efficiencies and topological attributes for controlling phase separation and film forming behavior. Through appropriate processing conditions involving very small quantities of solvent additives, it is possible to attain power conversion efficiencies of 7 %. The additive content is critical for managing the crystallite size of the donor domains.

8830-2, Session 1

Novel thiophene-based materials for highly efficient small molecule organic solar cells *(Invited Paper)*

Peter Baeuerle, Amaresh Mishra, Gisela Schulz, Roland Fitzner, Univ. Ulm (Germany)

Oligothiophenes represent an important class of compounds in the field of organic materials and have successfully been used as active components in organic solar cells (OSC).

On the basis of oligothiophenes, we are currently synthesizing and investigating novel organic semiconductors, which are applied in various types of organic solar cells. In this respect, terminally acceptor-substituted oligothiophenes have been further developed and tuned with respect to their electrooptical and self-organization properties. Efficiencies in vacuum-processed small molecule organic solar cells could be recently increased to (record) values of 7.2% for single junction and 12.0% for multi-stack cells. X-ray structure analyses guide the understanding how intermolecular interactions in the bulk correlate with device performance.

Systematic structural variation of the basic oligomers allowed for their use in solution-processed bulk-heterojunction solar cells achieving efficiencies of over 5%.

8830-3, Session 1

Cruciform and H-shaped small molecules for organic solar cells *(Invited Paper)*

Peter J. Skabara, Anto R. Inigo, Sasikumar Arumugam, Alexander L. Kanibolotsky, Iain A Wright, Ewan Cameron, Univ. of Strathclyde (United Kingdom)

A series of hybrid tetrathiafulvalene-oligothiophene compounds has been synthesized, where the tetrathiafulvalene unit is fused at each side to an end-capped oligothiophene chain of varying length. Each hybrid structure (1-3) has been studied by cyclic voltammetry and UV-vis spectroelectrochemistry, with the results for the smaller analogues (1 and 2) used to provide an explanation for the processes involved in septithiophene analogue 3. Further comparison is made to the corresponding half units, which lack the fulvalene core and contain just one oligothiophene chain, where appropriate. Finally, the hole mobility of quinquithiophene-TTF 2 was calculated from field effect transistor characteristics and its surface morphology was characterised by tapping mode atomic force microscopy. Compound 2 has been identified as the material with the best performance in BHJ OPV devices using C71PCBM as the electron acceptor. The device characteristics will be reported.

8830-4, Session 1

Design of molecular donors for organic solar cells *(Invited Paper)*

Philippe Blanchard, Jean C. Roncali, Univ. d'Angers (France)

Organic solar cells (OSCs) offer the possibility to develop low-cost and lightweight sources of photovoltaic electrical energy by means of simple technologies with low environmental impact.

Until now, the most efficient OSCs have been based on the heterojunction formed at the interface between an electron donor material an electron acceptor. Whereas a large part of the OSCs developed so far have used soluble π-conjugated (co)polymers as donor material, the polydispersity inherent to polymers can result in problems related to the reproducibility of the synthesis, purification and hence composition and electronic properties of the donor material. This context has contributed to stimulate intensive research work focused on the development of donor materials based on perfectly structurally defined conjugated molecules.

During the past few years, a huge number of molecular donors have been synthesized and evaluated in OSCs. Although this research effort has generated important progress in device efficiency, many molecular donors, especially those used in solution-processed OSCs are rather complex molecular structures of high molecular weight obtained by multi-step syntheses.

In this presentation the relationships between the molecular structure and the photovoltaic performances of various classes of donor materials based on push-pull molecules will be discussed. Special emphasis will be placed on the molecular design of materials combining structural simplicity, low molecular weight and synthetic accessibility, all factors that are believed to acquire a growing importance in the future context of industrial large-scale production of OSCs.

8830-5, Session 2

Vapor printed organic electrodes and semiconductors *(Invited Paper)*

Karen K. Gleason, Massachusetts Institute of Technology (United States)

Vapor printing has emerged as a promising technology for creating patterned layers of conducting and semiconducting conjugated polymers in a single step from their monomer vapors. Conformal polymer films over rough, low-cost substrates can be achieved at low processing temperatures. Additionally, vapor printing method removes the need to consider the effects of solubility or dewetting for materials integration into organic photovoltaics. Vapor printed poly(ethylenedioxythiophene) (PEDOT) is comprised only of earth-abundant elements and represents a low cost, flexible alternative to ITO. Organic photovoltaic cells with vapor printed PEDOT fabricated directly on unmodified paper substrates have achieved power conversion efficiencies > 2%. Post-deposition acid rinsing improves the ratio of dc to optical conductivity to 12. The stability also improves. Dopant exchange occurs with the acid anions leads to a higher degree of doping and enhances the stability of electrical conductivity. Additionally, unsubstituted polythiophene(PT) and poly(isothianaphthene) (PITN), which are insoluble and infusible, and thus typically difficult to process, have been vapor printed. The dedoped PT displays semiconducting behavior with an optical band bap of ~2 eV, while the bandgap for PITN is ~ 1 eV. Integration of these donor layers into photovoltaic devices will be demonstrated.

(submission invited by Dr. Paul Lane)

8830-6, Session 2

Heterogeneity and nano-scale electrical properties of ZnO thin film electron-selective interlayers in organic photovoltaic devices

Gordon A. MacDonald, The Univ. of Arizona (United States); Rajiv Giridharagopal, Univ. of Washington (United States); Micheal W. Liao, Xerxes K. Steirer, Kai-Lin Ou, The Univ. of Arizona (United States); Guozheng Shao, David S. Ginger, Univ. of Washington (United States); Neal R. Armstrong, The Univ. of Arizona (United States)

Efficient charge harvesting in organic solar cells (OPVs) is critically dependent upon the energetics of the contact/active layer interface(s), and the heterogeneity in composition, on sub-micron length scales, which can lead to localized recombination and loss of device performance. Conducting tip AFM (cAFM) and Scanning Kelvin Probe Microscopy (SKPM) techniques are uniquely suited to the study of electrical property heterogeneity in contact materials, such as ITO, and in the interlayer films which are often added to the contact to impart hole (e.g. NiOx) or electron selectivity (e.g. ZnO or TiO2). This presentation focuses on the role that compositional and electrical property heterogeneity can play in ZnO interlayer films, as revealed by scanning probe techniques, correlated with overall device performance. Sputter-deposited ZnO (spZnO) films were created at a variety of oxygen partial pressures, which varies both the mid-gap defect density in the ZnO film, and its conductivity (series resistance). Mild acid etching of these ZnO films was used to reveal the presence of different crystal faces of the wurtzite lattice in spZnO films, which possess different effective work functions – leading to different barriers to charge harvesting and quite heterogeneous electrical activity revealed by cAFM. We correlate this heterogeneity with changes in device performance and demonstrate the importance of minimizing this heterogeneity in a variety of ZnO or TIO2 films, whether they are deposited in vacuum or solution processed for scalable OPV applications.

8830-7, Session 2

The influence of contact properties on device performance in organic solar cells *(Invited Paper)*

Dana C. Olson, National Renewable Energy Lab. (United States)

Organic photovoltaics (OPVs) have become an attractive technology that offer a lower cost alternative to current commercial solar conversion technologies due to their potential for low temperature, large-area, and high-throughput manufacturing. Further barriers that must be overcome prior to commercialization lie in the development of OPV materials and device architectures to result in improved efficiency and stability. To achieve this, we are developing unique tools, design rules, and new materials for both active layers and selective contacts.

While the active layer materials are important for determining the ultimate performance, interfacial contact layers must be optimized both electronically and chemically for new active layer components. Such interfacial contacts are believed to improve device performance by a variety of mechanisms such as improved energy level alignment and charge carrier selectivity leading to improved charge extraction and reduced recombination. We are investigating the influence of the electronic properties of electron and hole transport layer (ETL and HTL) contacts on device performance to gain a greater understanding of the relative contributions of contact properties such as work function and band alignment. In addition, we are studying the effects of interfacial chemistry on local band alignment and device performance, by showing the deleterious effects of protonation in high performance solution processed small molecule solar cells. The independent control of work function and band alignment is shown to result in increased performance in both standard and inverted device architectures. Through this approach we are able to actively tune the contact properties to the ever changing properties of new active layer materials.

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8830-8, Session 2

High efficiency small molecular organic photovoltaic devices employing dual anode interfacial layers

Tyler Fleetham, Barry P. O'Brien, Arizona State Univ. (United States); John P. Mudrick, Univ. of Florida (United States); Jian Li, Arizona State Univ. (United States); Jiangeng Xue, Univ. of Florida (United States)

We demonstrated highly efficient small molecule organic photovoltaic devices using dual organic interfacial layers between the ITO anode and the organic donor material. The interfacial layers were composed of a spun-coat layer of poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS) followed by a small molecule organic layer of tetracene. The use of a small molecular templating layer, such as tetracene, proved to increase the molecular stacking of the subsequent phthalocyanine (Pc) based donor materials indicated by enhanced absorption in the region attributed to Pc aggregates, as well as increased crystalline domain sizes observed through AFM. Furthermore, the use of a PEDOT:PSS layer between ITO and a tetracene templating layer resulted in a change of the tetracene growth mode from a rough three-dimentional growth mode to a smooth, planar, two-dimensional growth mode that is better served for templating the active donor layer.

Upon application in planar heterojunction devices of PdPc and C60, an enhancement of over 80 percent in the donor contribution to the external quantum efficiency was observed. This enhancement has been attributed to the combination of exciton blocking by the higher bandgap tetracene layer, increased optical absorption, and enhanced exciton diffusion and charge transport resulting from the increased crystallinity. Furthermore, using a system of ZnPc as the donor material and C60 as the acceptor material, we fabricated planar-mixed heterojunctions with a PEDOT:PSS/ Tetracene dual anode interfacial layer. As a result we are able to fabricate devices with high JSC while maintaining a high FF and achieving power conversion efficiencies as high as 5.8%.

8830-9, Session 2

Polymer surface modification to produce low-work function electrodes for single- and multi-junction organic solar cells *(Invited Paper)*

Yinhua Zhou, Canek Fuentes-Hernandez, Jae Won Shim, Georgia Institute of Technology (United States); Jens Meyer, Princeton Univ. (United States); Anthony J. Giordano, Hong Li, Paul Winget, Theodoros Papadopoulos, Hyeunseok Cheun, Jungbae Kim, Georgia Institute of Technology (United States); Mathieu Fenoll, Georgia Institute of Technology (United States) and Solvay S.A. (Belgium); Amir Dindar, Princeton Univ. (United States); Wojciech Haske, Ehsan M. Najafabadi, Talha M. Khan, Hossein Sojoudi, Stephen Barlow, Samuel Graham, Jean-Luc Brédas, Seth R. Marder, Georgia Institute of Technology (United States); Antoine L. Kahn, Princeton Univ. (United States); Bernard Kippelen, Georgia Institute of Technology (United States)

Organic photovoltaic technologies have been the subject of active research and development over the past decades. Due to their ability to be processed at low temperature, over large areas, at potentially low cost, organic solar cells have experienced an accelerated development in recent years and have the potential to spawn a new generation of products with thin and flexible form factors. However, despite a steady progress in performance, many challenges and concerns about stability and cost remain before this emerging technology can unleash its full potential.

In this work, we show that surface modifiers based on polymers containing simple aliphatic amine groups substantially and universally reduce the work function of conductors including metals, transparent conductive metal oxides, conducting polymers, and graphene. The reduction arises from physisorption of the neutral polymer, which turns the modified conductors into electron-selective electrodes. These polymer surface modifiers are processed in air from solution, providing an appealing alternative to chemically-reactive low?work function metals. With this modification, various types of efficient single- and multi-junction solar cells, including all-plastic solar cells, have been demonstrated. The multi-junction solar cells with the new recombination layer show fill factor over 70% and power conversion efficiency over 8%.

The polymer surface modification turns out to be an efficient method to produce air-stable low?work function electrodes for organic solar cells. This approach should enable the mass production of low?work function electrodes from processes that are compatible with the large-area roll-to-roll manufacturing techniques required for the commercialization of low-cost organic and printed electronic devices.

8830-10, Session 2

Flexible and transparent graphene electrodes fabricated by residue-free doping transfer

Byoung Hoon Lee, Jong-Hoon Lee, Yung Ho Kahng, Nara Kim, Kwanghee Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

The breakthrough discovery of fabricating graphene flakes via mechanical exfoliation in 2004 began the experimental discovery of the outstanding physical and chemical properties of graphene. Consequently, graphene was envisioned as a highly functioning component for various applications, including flexible and transparent electrodes. However, three key issues—high-quality synthesis, residue-free transfer, and stable doping—need to be addressed for the practical application of graphene. Although the scaled-up synthesis of large-area graphene via chemical vapor deposition set a milestone in the development of graphene for applications, the latter two issues have not yet been satisfied. Here, we report a new graphene transfer process that solves these bottlenecks by using poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) as a new supporting layer. Because PEDOT:PSS is a well-known conducting polymer widely used as a hole transport layer in many organic optoelectronic devices, the graphene/PEDOT:PSS bilayer electrodes can be directly used for many applications without removing the supporting layer. Therefore, our new transfer method eradicates the residue contamination problem of conventional transfer methods. Furthermore, we confirm that the graphene was doped by the PEDOT:PSS with high stability during the new transfer process. Consequently, the new graphene/PEDOT:PSS electrodes demonstrate superior performance to both graphene electrodes fabricated via the conventional transfer method and indium tin oxide electrodes. Polymer solar cells with 5.5% (solid) and 4.8% (flexible) efficiencies were constructed using our new graphene electrodes. The combination of the remarkable, recently developed synthesis techniques with our transfer method will allow graphene to become a dominant electrode material in organic electronics.

8830-11, Session 3

Progress in making organic solar cells highly efficient and stable *(Invited Paper)*

Michael D. McGehee, Stanford Univ. (United States)

Some of the key questions regarding polymer solar cells are why certain bulkheterojunctions have internal quantum efficiencies higher than 90%, what is the optimal morphology and why fullerenes are by far the best electronic acceptors. We will show that in several highly efficient solar cells there is a three-phase morphology in which there are pure regions of polymer and fullerenes along with a mixed region. We will show that there are energetic offsets that push electrons and holes out of the mixed region and into the pure region. One can control the size and composition of the phases by adjusting factors such as the regioregularity and molecular weight of the polymer, the polymers sidechains, the donor:acceptor ratio, the choice of fullerenes, the use of processing additives and annealing conditions. We will show how one can decide what to adjust to get the ideal morphology and thereby obtain high energy conversion efficiency in solar cells. We will also discuss the mechanisms of degradation and polymer solar cells and how the lifetime can be extended.

8830-12, Session 3

The role of material interfaces on the efficiency and lifetime of organic solar cells *(Invited Paper)*

Elizabeth von Hauff, Albert-Ludwigs-Univ. Freiburg (Germany) and Fraunhofer-Institut für Solare Energiesysteme (Germany)

In this talk the role of contact interfaces on the efficiency and lifetime of polymer:fullerene bulk heterojunction (BHJ) solar cells is discussed. BHJ cells are most commonly fabricated on a transparent substrate coated with an ITO:PEDOT:PSS anode, and a low work function cathode is applied on the top of the stack. From the point of view of stability and performance this structure has significant drawbacks. Suboptimal vertical phase segregation during blend drying leads to an accumulation of polymer at the anode and fullerene at the cathode which reduces the collection of charge from the active layer and overall solar cell performance [1]. Additionally, the emergence of trap states at contact interfaces [2] can be traced to intrinsic instabilities of the anode materials. To locate loss sites in operational BHJJ devices we apply an equivalent circuit model of the BHJ cell based on extensive impedance spectroscopy analysis [3]. Finally, a stable ITO-free inverted solar cell architecture is demonstrated. Solar cell efficiencies are comparable to those obtained in the standard architecture [4].

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8830-13, Session 3

Stability investigations of inverted organic solar cells with a sol-gel processed ZnSrO or ZnBaO electron extraction layer

Olympia Pachoumi, Cheng Li, Yana Vaynzof, Kulbinder K. Banger, Henning Sirringhaus, Univ. of Cambridge (United Kingdom)

Stability of organic photovoltaic devices is a limiting factor for their commercialization and still remains a major challenge whilst power conversion efficiencies are now reaching the minimum requirements. The inverted organic solar cell architecture shows promising potential for improving significantly the cell's working lifetime however, often when solution processed ZnO is used as electron extraction layer (EEL), a light soaking step is required before the device reaches a non-permanent maximum performance. Here we show that by doping ZnO with Sr or Ba using sol-gel processing the light-soaking step is circumvented. In a model poly [3-hexylthiophene] (P3HT): [6, 6]-Phenyl C60 butyl acid methyl ester (PCBM) system we obtain EQE ~ 55% before UV exposure for ZnSrO or ZnBaO EELs as compared to 10% for undoped ZnO EEL. We have investigated the origin of this improvement by comparing the response to UV light of doped and undoped ZnO. Characterization includes electrical conductivity and x-ray photoemission spectroscopy studies on thin films, current-voltage experiments and electroabsorption (EA) spectroscopy to probe the built-in field in the devices. We will discuss how the results obtained and in particular the higher effective built-in field in doped ZnO devices (~1.5V) compared to a ZnO device (<0.5V) can help interpret the mechanism behind the device performance improvement with Sr and Ba doping of ZnO. Having designed a more passivated EEL we use high resolution optical spectroscopy [1] to further study the role of oxygen and water in degradation of a highly performing ZnSrO/PTB7:PC70BM system. [1] R. Di Pietro, H. Sirringhaus, Adv Mater 2012, 24, 3367.

8830-14, Session 3

The impact of organic impurities on OPV lifetime

William R. Mateker, Stanford Univ. (United States); Jessica Douglas, Univ. of California, Berkeley (United States); Clement Cabanetos, King Abdullah Univ. of Science and Technology (Saudi Arabia); Isaac T. Sachs-Quintana, Jonathan A. Bartelt, Eric T. Hoke, Stanford Univ. (United States); Abdulrahman El Labban, Pierre M. Beaujuge, Jean M. J. Fréchet, King Abdullah Univ. of Science and Technology (Saudi Arabia); Michael D. McGehee, Stanford Univ. (United States)

As the efficiency of organic photovoltaics continually improves, and is now as high as 12.0%, more research is directed at understanding and improving device lifetime. To what extent impurities affect device lifetime is currently under investigation. Metallic impurities are suspected to play a role in the lifetime of many organic semiconductor electronics. However, organic impurities can also hinder solar cell lifetimes. In this work, we study the lifetimes of solar cells made from batches of high and low molecular weight PBDTTPD. We find that high molecular weight PBDTTPD produces solar cells with a power conversion efficiency greater than 8.0%, but solar cells suffer a distinct degradation feature characterized by an S-shape in the current-voltage curve that increases in severity with time. An extraction barrier that forms at the cathode of the devices causes this degradation feature. Solar cells made from low molecular weight PBDTTPD, though less efficient, do not develop the characteristic S-shape degradation feature. However, this degradation feature is reproduced in these more stable solar cells by introducing a low molecular weight organic impurity. Finally, high molecular weight PBDTTPD, purified by column chromatography to reduce low molecular weight content, as compared to unpurified batches is shown to produce solar cells with comparable efficiencies and long lifetimes.

8830-15, Session 4

Towards high performance inverted polymer solar cells *(Invited Paper)*

Xiong Gong, The Univ. of Akron (United States)

Bulk heterojunction polymer solar cells that can be fabricated by solution processing techniques are under intense investigation in both academic institutions and industrial companies because of their potential to enable mass production of flexible and cost-effective alternative to silicon-based electronics. Despite the envisioned advantages and recent technology advances, so far the performance of polymer solar cells is still inferior to inorganic counterparts in terms of the efficiency and stability. There are many factors limiting the performance of polymer solar cells. Among them, the optical and electronic properties of materials in the active layer, device architecture and elimination of PEDOT:PSS are the most determining factors in the overall performance. In this presentation, I will present how we approach high performance of polymer solar cells. For example, by elimination of PEDOT:PSS, development of novel materials, fabrication of inverted polymer solar cells, we were able to observe over 50 % enhanced efficiency.

8830-16, Session 4

Optimizing and enhancing the efficiency of organic tandem solar cells by spatial photocurrent mapping

Andreas Pütz, Konstantin Glaser, Christian Sprau, Uli Lemmer, Alexander Colsmann, Karlsruher Institut für Technologie (Germany)

Record efficiencies of organic tandem solar cells recently approached 12%. The key to further efficiency improvements will be a smart choice of complementary absorbing materials for both subcells within a properly designed device architecture. As the device absorption is ruled by thin film interferences and as the matching of currents in both subcells is of major importance in order to achieve best device performance, the thicknesses of each layer in the device have to be optimized carefully. However, experimentally optimizing numerous functional layers in a tandem device on a sample-by-sample basis is a very time and material consuming task.

In this work we present a facile route to an efficient experimental screening of new materials and layer thickness optimization in solution processable tandem polymer photovoltaic devices. Therefore, we developed a method of fabricating tandem solar cells with a graded active layer thickness. Spatially resolved mapping of the solar cell short circuit current density for different light absorbing polymers under white light allows for a quick conclusion about the optimum active layer thickness within the device. When plotting the short circuit current density versus the local active layer thickness, the influence of the thin film interference pattern within the device becomes apparent. The measured short circuit current densities are in very good accordance with optoelectronic device simulations for all layer thicknesses.

In tandem solar cells, this technique is an efficient tool for matching both subcell currents with only little experimental effort and hence building tandem solar cells with high power conversion efficiencies.

8830-17, Session 4

Four-terminal organic solar cell modules with increased annual energy yield *(Invited Paper)*

Robert Gehlhaar, David Cheyns, Luuk Van Willigenburg, Afshin Hadipour, IMEC (Belgium); Roshanak Radbeh, Solvay S.A. (Belgium); Tom Aernouts, IMEC (Belgium)

With the rapidly improving efficiencies of organic solar cells and current records of 12% new device designs are needed to transfer these achievements from small area lab demonstrators to large area modules. Nowadays, the record organic solar cells consist of tandem structures where two complementary absorbing solar cells are combined in order to efficiently harvest light from different parts of the solar spectrum. The vertical assembly of two devices demands sophisticated optical and electrical alignments . Optically, the layer stack has to be optimized to maximize the absorption of a certain spectral range in the corresponding subdevice. The serial electrical connection requires a current matching of the two subcells. An optimum achieved mainly by a variation of the layer thicknesses within the stack is limited to certain light spectrum and angle of incidence.

We present a four-terminal organic solar cell module that shows a low dependence on the incident light conditions. A semi-transparent and an opaque submodule with aperture areas of 16cm2 each are mechanically combined to a device with the same aperture area that does not require additional encapsulation. The fabrication process includes the development of a mechanical scribing process for the efficient module patterning leading to a geometrical fill factor of 94%. We are going to present semitransparent submodules with 5.0% efficiency which in combination with an opaque submodule give devices with 6.5% efficiency.

The presentation closes with a view on the total annual energy yield of the presented design in comparison to conventional structures.

8830-18, Session 4

Efficient tandem polymer solar cells with a PEDOT:PSS/nonconjugated polyelectrolyte intermediate layer

Jinho Lee, Hongkyu Kang, Jeamin Kong, Kwanghee Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

We report efficient tandem polymer solar cells (TPSCs) using a PEDOT:PSS/nonconjugated polyelectrolytes (NPEs) as an intermediate layer (IML). By applying the NPEs to the electrode surfaces of the TPSC structure, the work functions (WFs) of indium tin oxide (ITO) cathode for front subcell and a poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) cathode for back subcell are significantly reduced to 3.95 eV and 3.88 eV, respectively. Kelvin probe (KP) and x-ray photoelectron spectroscopy (XPS) studies indicate that protonated amines of the NPEs are responsible for the WF changes of the electrodes. Furthermore, we confirm that by increasing the degree of protonation of the amine group in NPEs, the electrode WFs can be dramatically reduced. Because the modified WFs of the electrodes form ohmic contacts with the lowest unoccupied molecular orbital (LUMO) level of fullerene and induce strong electric fields inside each subcells, we successfully demonstrate the highly efficient TPSCs with power conversion efficiency of 7.8 %.

8830-19, Session 4

Fullerene based organic Schottky-junction devices for large open circuit voltage organic solar cells

Jinsong Huang, Bin Yang, Univ. of Nebraska-Lincoln (United States)

Generally it is believed that Schottky-junction structure cannot be used in organic photovoltaic devices (OPVs) for a reasonably high efficiency. In this manuscript we reported the fullerenes based Schottky-junction devices which output a larger open circuit voltage (Voc) (0.85-0.95 V) than most of bulk heterojunction (BHJ) OPVs, i.e. 0.60 V for P3HT:PCBM devices. A small concentration of P3HT doping (5 wt%) won't change the Voc while increases the short circuit current (Jsc) to be comparable to that of P3HT:PCBM BHJ devices. This Schottky-junction device has three major advantages: First, since its Voc is governed by the Fermi level of the fullerene and the work function of anode, a larger Voc of more than 1 V can be potentially achieved with easily tuning the work function of the anode; Second, the resulted high efficiency of 5% at low light intensity, much larger than that of P3HT:PCBM BHJ devices, makes it very attractive for the application of indoor light energy harvesting; Third, this device is much more stable than BHJ OPVs due to less donor polymer aggregation. We believe this work will raise the broad interest in OPV society to explore the potential of Schottky-junction structure for high efficiency and long lifetime OPVs.

8830-20, Session 4

New insights on the role of the donor material in C60-based Schottky-junction small molecule organic solar cells

Sibi Sutty, Graeme M. Williams, Hany Aziz, Univ. of Waterloo (Canada)

C60 based Schottky-junction solar cells have shown promising performance with high power conversion efficiencies. Zhang et al. reported PCEs as high as 5.23% with a Voc of 0.91V for a cell with the structure: ITO/MoO3/C70:TAPC (5%)/BPhen/Al. However, there are several unanswered questions about the role of the Schottky-junction and the donor material in enabling high photovoltaic performance. In literature, the Voc of these cells was observed to be independent of the donor material suggesting that it is determined by the band-bending present at the ITO/MoO3/C60 interface. The enhanced Jsc seen with the addition of donor material has been attributed to the dissociation of Frenkel excitons formed in C60. The exact mechanism of hole extraction is however unclear. Furthermore, only a limited range of materials were tested. In order to further understand the factors governing the performance of these OSCs, we carried out a systematic comparative study utilizing a range of materials of various HOMO and LUMO levels as donors. The materials are selected to produce different HOMO-LUMO offsets with C60. The effect on Voc and charge extraction were studied. Contrary to reports in literature, we found that the Voc is affected by the HOMO-LUMO difference between the donor material and C60. We also found that the enhanced Jsc can be achieved by means of altering device architecture. In light of these findings, a revised explanation for the operation of Schottky-junction cells will be presented.

8830-21, Session 5

Light management approaches in nanostructured organic semiconductor thin films *(Invited Paper)*

Deirdre M. O'Carroll, Gary Cheung, Christopher Petoukhoff, Rutgers, The State Univ. of New Jersey (United States)

In this presentation, we will discuss two approaches for light management in organic thin film photovoltaic devices. We will show that binary and ternary blend thin films of organic conjugated polymer and oligomer materials can double the fraction of solar energy absorbed compared to single component thin films. Additionally, photoluminescence measurements show that excitonic energy transfer efficiency between the different materials within the thin film blends can approach 100 % by optimizing the relative fraction of each material in the blend. We propose that such ternary blends can offer an alternative to more complex tandem organic photovoltaic device architectures.

Additionally, light management though the application of plasmonic electrodes will be presented as a route to further improve the effective absorption depth and generation rate in inverted bulk-herterojunction organic photovoltaic devices (BHJ-OPVs). We will discuss our recent theoretical and experimental results on the performance and fabrication of nanostructured plasmonic electrodes. We have found that the interaction of light with plasmonic nanostructured electrodes can result in three distinct phenomena that can affect the device performance: 1) localized, resonant electromagnetic field enhancement; 2) light scattering; and 3) propagating electromagnetic surface waves. The first effect provides 'hot spots' within about 50 nm of the nanostructured electrodes, which can increase the generation rate of the charge carriers in semiconductors placed nearby. The second and third effects increase the optical path length in the active layer, increasing total light absorption. All of these effects combined can potentially increase the overall efficiency of BHJ-OPVs if designed properly.

8830-22, Session 5

Morphology and growth of organometal halide perovskite films for highly efficient hybrid solar cells

Giles E. Eperon, Victor M. Burlakov, Pablo Docampo, James M. Ball, Michael M. Lee, Henry J. Snaith, Univ. of Oxford (United Kingdom)

Solution-processable semiconducting perovksite materials have recently shown significant promise as absorbers in sensitized solar cells, and it has been found that they can also act as electron or hole transporters [1,2,3]. A key challenge in this new field is optimising solar cell architecture to enable maximum efficiencies; in the specific case of methylammonium lead halide perovskite a high-temperature processed mesostructured layer is used for the best performing devices [4]. Since the perovskite absorber is capable of absorbing light, generating free charge and transporting electrons, we no longer require a thermally sintered mesoporous oxide to enable efficient charge collection; we have been able to eliminate all sintering steps in the manufacture of these solar cells. However, the current 11% efficient devices are still composed of inhomogeneous layers. Challenges in fabrication of continuous perovskite films arise from the development of pinholes within the film upon annealing. These occur due to the interplay between perovskite surface energies with the substrate and air, the effects of rapid crystallisation upon drying, and stoichiometry-driven mass loss.

Here we report on a detailed study on the growth and morphology of the methylammonium lead halide perovskite. We have developed and experimentally verified a mathematical model describing dynamic pinhole growth in such films. Using the insights gained we have optimised the formation of continuous perovskite films, and from this we have fabricated hybrid methylammonium lead halide perovskite devices demonstrating efficiencies in excess of 10%, with the active layer fully processed below 150°C.

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8830-23, Session 5

Highly transparent polymer solar cells achieving 5% efficiency

Chun-Chao Chen, Yang Yang, Letian Dou, Univ. of California, Los Angeles (United States)

In this work, we demonstrated a high-performance solution-processed transparent polymer solar cell. So far, no significant progress has been made on the transparent PV device due to the lack of transparent PV materials and top electrodes. Upon the utilization of high performance low bandgap polymer, the photoactive layer absorbs more near-infrared light while being less sensitive to visible light. The transparent electrode is a fully solution-processed conducting silver nanowire-based composite film with indium tin oxide nanoparticles. With this combination, we have achieved 5% power-conversion efficiency for the fully solution-processed transparent solar cells on indium-tin-oxide-coated glass substrates.

8830-24, Session 5

Patternable conjugated polymers for organic solar cells

Peter Strohriegl, Philipp Knauer, Christina Saller, Esther Scheler, Univ. Bayreuth (Germany)

Semiconducting polymers have gained large interest during the last two decades. In view of applications in OLEDs and Organic Solar Cells (OSCs) patterning of conjugated polymers to small feature sizes is of particular interest.

A number of patterning techniques are known, which can be divided into top-down and bottom-up approaches. A typical bottom-up approach uses the self-assembly of materials (e.g. block copolymers). With this strategy very small feature sizes are accessible, but there are severe limitations in the shape of possible structures, which are predetermined by the interplay of forces between different materials in the self-assembly process.

The formation of patterns with arbitrary shape is a big advantage of top-down methods like printing and lithography. A high resolution of much less than 100 nm can be obtained using both photolithography and special printing techniques like microcontact printing.

We present a lithographic approach for the formation of polymer multilayers and microstructures from photocrosslinkable polyfluorenes and polyfluorene copolymers. For this purpose we synthesised fluorene based polymers with photopolymerisable acrylate groups. Subsequent photopolymerisation leads to densely crosslinked and insoluble polymer films. Using a µm-sized photoresist test mask patterns with a minimum size of 700 nm are formed [1-3]. Meanwhile we have extended the synthesis to photocrosslinkable low bandgap polymers like PCDTBT with crosslinkable oxetane units. First work on how to use patterned organic semiconductors in organic solar cells will be presented.

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8830-25, Session 5

Flow techniques for the synthesis of semiconducting polymers

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There is an urgent need for improved methods of producing sizeable volumes of high-quality semiconducting polymers for large area plastic electronics. We have recently developed a stable droplet reactor for synthesising poly(3-hexylthiophene) (P3HT). Using this approach it is possible to tune molecular weight and regioregularity with superior control to conventional batch methods. Here we present an overview of techniques for polymer synthesis in flow, showing how the exploitation of reactions on the micro-scale leads to significantly enhanced rates of reaction, synthetic control and reproducibility and narrowing of polydispersity.

Our method sees the injection of monomeric species and catalysts into a flowing stream of inert fluid fluoropolymer in a narrow PTFE capillary, creating sub-microlitre sized reaction droplets. The droplet method overcomes a common problem with continuous flow methods where reactors are liable to clogging. The inert fluoropolymer has the effect of preferentially wetting the reactor surface preventing the reaction mix from interacting with the surface, eliminating reactor ageing. Initial tests have shown that it is possible to produce material at rates approaching 100 g/day with significant potential for further scaling.

8830-26, Session 6

Diketopyrrolopyrrole based molecular semiconductors: versatile materials for organic solar cells and ambipolar field-effect transistors *(Invited Paper)*

Satish Patil, Indian Institute of Science (India)

Since the inception of bulk hetero junction (BHJ) concept there has been tremendous growth in organic photovoltaics (OPV) and produced device with efficiencies up to 9.8%. Major criteria for this remarkable performance originate from adaption of donor-acceptor (D-A) or donor-acceptor-donor (D-A-D) concept in design of low band gap polymers. With a myriad of donor type of materials synthesized the major focus of various research groups lies in using diketopyrrolopyrrole (DPP) as an acceptor and combining with electron rich units like phenyl, thiophene and other aromatic heterocycles to generate novel D-A and D-A-D type copolymers with high efficiency. Focus of talk is on synthesis of DPP-DPP based low band gap D-A-D type copolymers. This novel idea of self-coupling thiophene DPP with itself, each unit having different alkyl chain, has yielded copolymers with high molecular weight, low PDI and better overlap with solar spectrum. Top gate OFET by using these polymers exhibited highest n-type mobility (3 cm2V–1s–1) reported till date.

8830-27, Session 6

Complementary absorbing star-shaped small molecules for the preparation of ternary cascade energy structures in organic photovoltaic cells

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Two anthracene-based star-shaped conjugated small molecules, 5',5''-(9,10-bis((4-hexylphenyl)ethynyl)anthracene-2,6-diyl)bis(5-hexyl-2,2'-bithiophene), HBantHBT, and 5',5''-(9,10-bis(phenylethynyl)anthracene-2,6-diyl)bis(5-hexyl-2,2'-bithiophene), BantHBT, were used as electron-cascade donor materials by incorporating them into organic photovoltaic cells prepared using a poly((5,5-E-alpha-((2-thienyl)methylene)-2-thiopheneacetonitrile)-alt-2,6-[(1,5-didecyloxy)naphthalene])) (PBTADN):[6,6]-phenyl-C71-butyric acid methyl ester (PC71BM) blend. The small molecules penetrated the PBTADN:PC71BM blend layer to yield complementary absorption spectra through appropriate energy level alignment and optimal domain sizes for charge carrier transfer. A high short-circuit current (JSC) and fill factor (FF) were obtained using solar cells prepared with the ternary blend. The highest photovoltaic performance of the PBTADN:BantHBT:PC71BM blend solar cells was characterized by a JSC of 11.0 mAcm–2, an open circuit voltage (VOC) of 0.91 V, a FF of 56.4%, and a power conversion efficiency (PCE) of 5.6% under AM1.5G illumination (with a high intensity of 100 mW–2). The effects of the small molecules on the ternary blend were investigated by comparison with the traditional poly(3-hexylthiophene) (P3HT):[6,6]-phenyl-C61-butyric acid methyl ester (PC61BM) system.

8830-28, Session 6

Solution processable small molecules for organic photovoltaics

Scott E. Watkins, Kevin N. Winzenberg, Gavin E. Collis, Peter Kemppinen, Thokchom B. Singh, Fiona H. Scholes, Commonwealth Scientific and Industrial Research Organisation (Australia)

This paper will discuss the issue of molecular association with regards to small molecule donor material and its effect on the open circuit voltage in organic solar cells based on these materials. The paper will also introduce a new class of small molecule semiconductors based on solubilised indene derivatives. Their performance as N-type materials in solution-processed organic solar cells will be discussed. The development of alternatives to commonly used fullerenes enables the exploration of a wider parameter space in which to improve the performance of devices. A family of derivatives based on the parent compound, F8IDT, have been prepared through simple synthetic routes upto 20g in scale. Solution processed BHJ OPVs have been prepared using F8IDT as the acceptor and P3HT as the donor. Power conversion efficiencies in excess of 2% will be reported. We will also show correlations between the calculated and measured LUMO energy levels and the device open circuit voltages that highlight the validity of our approach to the design of new n-type materials. Finally, physical and electronic characterisation data will be presented to discuss the influence of molecular structure on device performance.

8830-29, Session 6

Improving the performance of P3HT/PCBM solar cells with squaraine dye

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Expanding the spectral absorption breadth and efficiently harvesting excitons are crucial towards creating highly efficient polymer solar cells. A common strategy is to adopt a tandem structure consisting of multiple subcells. However, in polymer tandem cells it is technically challenging to design and optimize each subcell and the interconnecting layers between the subcells. Here we describe an alternative strategy to realize broad-band light harvesting in poly(3-hexylthiophene) (P3HT)-based solar cells. We introduce the use of squaraine dye molecules that play a dual role towards improving P3HT-based solar cells. The first benefit is an increase in the spectral absorption in the near infrared region. The second advantage is the collection of excitons close to the interfacial heterojunctions via Förster resonance energy transfer (FRET). Unlike traditional multi-blend systems, where each donor works independently in separate spectral responses, FRET-based systems enable the effective use of multiple donors with significant improvements in light absorption and conversion. Our ultrafast transient absorption experiments show that the excitation energy from P3HT can be transferred rapidly (within a few picoseconds) and efficiently (up to 96%) to the squaraine via FRET. Thus, the external quantum efficiency increases in both the visible and the near-infrared regions. In addition, nano-morphology of the photoactive layer with an interpenetrating network is well developed by SQ. As a result, the overall power conversion efficiency is dramatically improved from 3.27% to 4.51%. This architecture opens up a new paradigm towards transformative improvements of polymer solar cells.

8830-30, Session 6

Probing charge carrier dynamics in organic solar cells based on merocyanines

Steven Graf, Martin R. Lenze, Julian Krumrain, Dirk Hertel, Klaus Meerholz, Univ. zu Köln (Germany)

Highly efficient organic bulk heterojunction (BHJ) solar cells can be produced by various methods such as coating from solution (SOL) or depositing under high vacuum conditions (VAC).

We investigate merocyanines (MC), a class of low-molecular-weight colorants, as donor material in organic BHJ solar cells. These small molecules are processable via both deposition techniques, showing remarkable PCEs beyond 4% for SOL-processed and 6% for VAC-processed devices.

Since MC solar cells suffer from rather poor fill factors of well below 50%, it is mandatory to obtain a better insight into physical processes such as charge carrier generation, transport and recombination. We use steady state and time resolved photoluminescence (PL) spectroscopy to examine emissive states in pure and blended merocyanine thin films. While we find emission of both thermally populated states as well as states with strong CT character in pure films, distinct quenching of an emissive CT state between the MC donor and the PCBM acceptor can be spotted in blended films under presence of an electric field. By varying the donor/acceptor composition in devices, the influence of morphology on the solar cell parameters is illustrated and further studied by temperature dependent current-voltage and external quantum efficiency (EQE) measurements. The recombination and transport dynamics of free charge carriers are probed by the photo-CELIV technique. Despite the high dipole moments of MC molecules, optimized devices show decent charge-carrier mobilities and densities at room temperature. However, bimolecular recombination of free charge carriers at weak internal fields appear to be the highest loss channel in MC solar cells.

8830-48, Session PWed

Investigate the role of the active layers structures and morphology in the performance of the organic solar cell devices

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Several CuPc/PTCDI-C8 films with different structures (co-deposited, layered and bilayer) were prepared and their structural properties were studied using X-ray diffraction. In order to study the effects of the active layers' structures on the performance of the device, organic solar cells based on these films were fabricated and their electrical characteristics have been explored. Absorbed prominent diffraction peaks for CuPc/PTCDI-C8 bilayer films indicate the formation of higher degree of crystallinity for this structure compared to the films with layered or co-deposited structures. This crystallinity results in higher device performance due to reduced recombination losses and microscopic shorts within the devices.

8830-50, Session PWed

Loss mechanisms in hybrid plasmonic bulk heterojunction organic solar cells

Bo Wu, Tze Chien Sum, Xiangyang Wu, Nripan Mathews, Hong Jin Fan, Edwin Kok Lee Yeow, Cao Guan, Kong Fai Tai, Nanyang Technological Univ. (Singapore)

Controversy has been found over the effects of organic ligand encapsulated plasmonic nanoparticles blended in bulk heterojunction organic solar cells where both enhancement and degradation in performance have been reported. Herein, using a suite of transient optical spectroscopy and electrical characterization techniques, we have revealed the evidence of traps being responsible for the performance degradation in organic solar cells fabricated with oleylamine-capped silver nanoparticles (AgNPs) blended in poly (3-hexylthiophene):[6,6]-phenyl-C 61-butyric acid methyl ester (P3HT:PCBM) active layer. Traps can introduce two different loss mechanisms: (a) interfacial traps at the interface regions of P3HT:PCBM domains that are dominated by the Shockley-Read-Hall recombination; and (b) intra-domain traps located within a phase separated domain increase the energetic disorder of the density of states, thereby impeding the charge hopping. The new insight would resolve the existing controversy and provide guidelines for the design of hybrid plasmonic organic solar cells.

8830-52, Session PWed

Transient spectroscopies in studying loss mechanisms in silver nanoparticles-blended bulk heterojunction organic solar cells

Bo Wu, Xiangyang Wu, Cao Guan, Kong Fai Tai, Edwin Kok Lee Yeow, Hong Jin Fan, Nripan Mathews, Tze Chien Sum, Nanyang Technological Univ. (Singapore)

The effects of organic ligand encapsulated plasmonic nanoparticles blended in bulk heterojunction organic solar cells have been controversial. Both enhancement and degradation in performance of organic solar cells have been reported. Herein, a comprehensive suite of transient optical spectroscopy and electrical characterization techniques were used to uncover that traps are responsible for the performance degradation in organic solar cells fabricated with oleylamine-capped silver nanoparticles (AgNPs) blended in poly (3-hexylthiophene):[6,6]-phenyl-C 61-butyric acid methyl ester (P3HT:PCBM) active layer. The trap-assisted recombination rate was found to be increased by three times upon incorporation of AgNPs. Besides, charge transport will also degrade due to the increased disorder in the density of states (DOS). These new insights would resolve the existing controversy and provide guidelines for the design of hybrid plasmonic organic solar cells.

8830-53, Session PWed

Application of DSSC dyes as efficient donor materials for small-molecule-based organic photovoltaics

Xiao-Feng Wang, Yamagata Univ. (Japan)

A donor-acceptor (D-A) type dye-sensitized solar cell (DSSC) dyes, were used as an electron donor in organic solar cells (OSCs). For bulk-heterojunction (BHJ) type OSCs with PCBM as electron acceptor, the power conversion efficiency (PCE) is sensitive to the amount of donor in the donor/PCBM blend film. In order to improve the PCE of DSSC dye based OSCs, bilayer- and bulk-heterojunction configuration with C70 as electron acceptor has been employed. By optimization of the thickness of active layer and variation of the electron- and hole-transport layers, the highest PCE of up to 4.5% with a Jsc of 9.1 mA cm-2, a Voc of 0.89 V, and an FF of 0.56 was achieved under AM 1.5G solar illumination (100 mW cm-2)

8830-54, Session PWed

Effects of pressure on contact between layers in organic solar cells

Benjamin Agyei-Tuffour, African Univ. of Science and Technology (Nigeria)

This paper investigates the effects of pressure on the contacts between layers organic solar cells with poly (3-hexylthiophene):phenyl-C61-butyric acid methyl ester (P3HT:PCBM) as active layer. The contacts between the layers are modeled using analytical concepts and finite element models. The potential effects of surface roughness and dust particles are modeled along with the effects of lamination pressure and adhesion energy. The results show that, improved contact and adhesion decreases the void length while increasing the contact length. The contacts associated with the interfaces between the active layer (P3HT: PCBM) and the hole/electron injection layer Poly(3,4-ethylenedioxythiophene): Poly (styrenesulphonate) (PEDOT.PSS) and Molybdenum Trioxide (MoO3) are also compared. The implications of the results are discussed for the design of stamping/lamination processes for the fabrication of the organic solar cells.

8830-55, Session PWed

Surface plasmon resonance of carbon dot-supported silver nanoparticles

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The coupling of surface plasmons and excitons in organic materials can improve the performance of organic optoelectronic devices.1,2 Here, we fabricate solution-processed polymer light-emitting diodes (PLEDs) and polymer solar cells (PSCs) using carbon dot-supported silver nanoparticles (CD-Ag NPs). The surface plasmon resonance effect of CD-Ag NPs allows significant radiative emission and additional light absorption and achieves a remarkably enhanced current efficiency (CE) of 27.16 cd A-1 and a luminous efficiency (LE) of 18.54 lm W-1 in PLEDs as well as a power conversion efficiency (PCE) of 8.31% and an internal quantum efficiency (IQE) of 99% in PSCs compared with devices without CD-Ag NPs (CE = 11.65 cd A-1, LE = 6.33 lm W-1 in PLEDs and PCE = 7.53%, IQE = 91% in PSCs). To the best of our knowledge, these device efficiencies in PLEDs and PSCs with CD-Ag NPs are record-high values in plasmonic polymer optoelectronic devices with metal nanoparticles.

8830-57, Session PWed

Effects of ionic liquid molecules in hybrid PbS quantum dot - organic solar cells

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We investigated the effect of ionic liquid molecules (ILMs) in quantum dot-organic hybrid solar cells. The insertion of an ILMs layer between PbS and PCBM can shift the band edge of PCBM closer to the vacuum level of PbS due to spontaneous dipole polarization. Owing to this new architecture, improvements in device performance were achieved, including an increase in VOC from 0.41 V to 0.49 V, FF from 0.48 to 0.59 and PCE from 1.62% to 2.21% compared to reference devices under AM 1.5G illumination at 100 mW cm-2. We observed that treatment of the PbS layer with ILMs causes a significant increase in work function from 3.58 eV to 3.93 eV. Furthermore, the ILMs layer minimizes the contact resistance between PbS and PCBM due to the improved compatibility between the two layers, confirmed as a decrease in charge transfer resistance as measured by electrical impedance spectroscopy.

8830-58, Session PWed

An optimization algorithm for designing robust and simple antireflection films for organic photovoltaic cells

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We propose a method to design multilayer antireflection (AR) structure, which has robustness against variations in layer thicknesses, for organic solar cells. When a set of available materials are given, the proposed method searches for the material and thickness of each AR layer to maximize the short-circuit current density (Jsc). The algorithm is composed of the following two steps. The first step is to perform global search of the AR structure through the optical analysis using the characteristic matrix method. Here, we use a hybrid optimization scheme that combines the quasi-newton method with many random initial points, for searching the solutions of layer thicknesses, and exhaustive search, for searching those of material combination. This algorithm allows for obtaining a set of solutions, including optimal and quasi-optimal solutions, at the same time, so that we might clearly make comparison between them. In the second step, the effects of deviations in the thicknesses of the AR layers are examined for the (quasi-) optimal solutions obtained by the previous step. The expectation of the decrease in the AR performance is estimated by calculating the changes in Jsc when the thicknesses of all AR layers are varied independently. We showed that some of quasi-optimal solutions may have simpler layer configuration and can be more robust against the deviations in film thicknesses, than the optimal solution. This method indicates the importance of actively searching valuable, non-optimal solutions for practical design of AR films.

8830-60, Session PWed

Evaluation of exciton diffusion in triphenylamine-cored derivatives

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Understanding and control of the energy migration is critical for enhancing efficiency of organic electronic devices like light emitting diodes, solar cells etc. Exciton diffusion length is particularly important for organic solar cells, since it reflects the amount of photogenerated excitons that are able to reach donor-acceptor interface and contribute to the photocurrent, and hence, to the device efficiency.

In this work, exciton diffusion in a series of triphenylamine derivatives exhibiting excellent hole drift mobilities (up to 0.02 cm2/Vs) [1] was investigated. Systematic investigations of the exciton diffusion length (L) vs the number and type of the phenylethenyl sidearms linked to the triphenylamine core were carried out. The determination of L was based on the evaluation of fluorescence quenching efficiency in the triphenylamine films with randomly distributed quenchers. For the evaluation, Monte Carlo simulations of the PL transients in triphenylamine/quencher blends with different quencher concentration were performed [2]. The obtained data revealed that the increasing number of phenylethenyl sidearms generally implies larger exciton diffusion coefficient (up to 5.4•10^-4 cm2/s) and also results in the increased exciton diffusion length from 3 nm to 11 nm, most likely due to the denser sidearm network formed. Estimated exciton diffusion lengths are found to be comparable or higher as those of the narrow bandgap polymers employed in modern bulk heterojunction solar cells.

[1] T. Malinauskas, et al., Chem. Commun. 47, 7770-7772 (2011).

[2] O. V. Mikhnenko, et al., Energy Environ. Sci. 5, 6960–6965 (2012).

8830-61, Session PWed

Highly efficient polymer solar cell modules fabricated by slot-die coating method

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Slot-die coating is one of the promising methods for fabricating

large-area polymer solar cells (PSCs) due to its compatibility with roll-to-roll printing and one-dimensional direct patterning. In this study, we investigated correlations between conformal film morphology of intermixed poly(3-hexylthiophene)(P3HT) and fullerene derivative [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) bulk-heterojunction(BHJ) material and universal control factors in slot-die coating method, such as shim length, substrate temperature, and coating speed. The observed correlation equation is better matched to the meniscus coating parameter equation rather than to the traditional high-viscosity extrusion slot-die coating parameter equation. The slot-die coated PSCs with PCE values of 3.07% were successfully fabricated. In addition, high-throughput (5.0 m/min), slot-die-coated PSCs exhibited a uniform average PCE of 2.58%. Also, highly efficient polymer solar cell modules are fabricated by using slot-die coating method.

8830-62, Session PWed

Role of additional PCBM layer in inverted bulk heterojunction solar cells

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High performance inverted organic bulk heterojunction solar cells were demonstrated using a novel polymer, polythienothiophene-co-benzodithiophenes (PTB7-F20), as a donor and phenyl-C61-butyric acid methyl ester as an acceptor. Wet-chemically prepared ZnO and poly(3,4-ethylenedioxythiophene):poly-(styrenesulfonate) (PEDOT:PSS) were used as buffer layers. Particularly, for ZnO layer, self-organized ripple nanostructure were introduced to enhance more light absorption. In addition, in order to induce more easy extraction of electrons, additional PC61BM layer was inserted between active layer and ZnO buffer layer. Inverted BHJ solar cell with additional PC61BM layer exhibited almost 10% higher power conversion efficiency of 7.4% compared to the solar cell without additional PC61BM layer. Unlike our expectation that transit time would have been improved by additional PC61BM layer, intensity modulated photovoltage spectroscopy (IMVS) and intensity modulated photocurrent spectroscopy (IMPS) results indicated that recombination time was more greatly improved with additional PC61BM layer. Based on these IMPS, IMVS results, we concluded that enhanced PCE was attributed to quenching electron–hole recombination at surface defects of ZnO ripples.

8830-63, Session PWed

Understanding the thickness dependent photocurrent spectra of organic bulk heterojunction solar cells

Buddika K. Abeyweera, Bruce W. Alphenaar, Univ. of Louisville (United States)

Photocurrent spectra are measured for bulk heterojunction organic solar cells having a range of active layer thicknesses. Normalized by the number of incident photons, the photocurrent peak red shifts with respect to the absorption maximum as the sample thickness increases. The shift in photocurrent peak can be understood by modeling the carrier extraction as a function of sample thickness. Carriers generated on the sample surface undergo enhanced recombination compared with those in the bulk. For example, bimolecular recombination predominately affects charge generated near the top contact where the carrier concentration is high; recombination of excitons through contact interface states occurs only for photoexcitation near the surface; and recombination of free electrons is larger for charge generated away from the back electron collecting contact. For thick samples, an increased percentage of light away from the absorption maximum contributes to the photocurrent due to carriers generated in the bulk of the sample. Suffering fewer losses than surface generated carriers, the bulk carriers have a relatively large influence on the photocurrent. Fitting the photocurrent spectra as a function of sample thickness differentiates between photocurrent collected from carriers generated in the bulk of the sample versus those generated at the surface, and provides a measure of the electron collection length and the surface enhanced recombination. The variation in the electron collection length with active layer composition and contacting parameters can then be used as a guide for optimization of the solar cell structure

8830-64, Session PWed

Increase in solar cell performances of transparent conductive oxide-less cylinder dye-sensitized solar cells: simulation on light harvesting, increase in efficiency, and total electric power generation in a day

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It is expected that cylinder type dye sensitized solar cells have an advantage over flat type dye-sensitized solar cells in terms of encapsulation. We have already reported transparent conductive oxide-less cylinder dye-sensitized solar cells (TCO-less cylinder DSC) fabricated inside a glass tube (6.1 % efficiency). The cell consists of a silicone tube (a supporter of a counter electrode)(A), stainless metal mesh tube covered with thin Ti layer (counter electrode)(B), a gel electrolyte tube(C), a porous titania layer stained with dyes(E) fabricated on a stainless metal mesh tube covered with thin Ti layer(D) acting as electron recombination blocking layer, and a plastic tube cover or glass tube cover(F). At first, the efficiency was only 3.39%. Laser beam induced current (LBIC) curves measured at 633 nm were flat across the diameter direction of the cylinder. However, large decreases of LBIC current were observed when the 405 nm laser was used. The large decreases in LBIC were explained by light harvesting loss caused by I-/I3- species (absorption at around 400 nm) which exist in space between an outside wall and a porous titania layer. In order to remove the space consisting of electrolyte, a thermally shrinkable tube (G) was employed as a cover tube(F). The efficiency increased from 3.38% to 5.08%. In addition, the space was filled with a transparent thin plastic layer, which inhibits electrolyte from presenting between the space. By inserting the transparent plastic layer, IPCE values in the area of 400-500 nm increased drastically. The results were explained by simulation results on light harvesting properties. Solar cell performances of TCO-less cylinder DSC with reflector were evaluated. It was found that constant LBIC current was observed across the curved reflector, suggesting that efficient light harvesting were carried out by the curved reflector. The shape of the reflector by light harvesting simulation would be presented. Total electric power of the TCO-less cylinder DSC in a day was compared to that of TCO-less flat DSC. The former was 1.3 times higher than the latter, demonstrating the high light harvesting ability of the cylinder solar cells.

8830-65, Session PWed

High performance PEDOT:PSS films prepared through a treatment with fluoro compounds and their application in polymer solar cells

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International concern about global warming and climate change due to emission of CO2 led to intense search for clean and renewable energy technologies such as photovoltaics. Polymer solar cells (PSC's) have received much attention as a promising clean and green energy

technology and the power conversion efficiency have steadily increased. There are several ways to improve the device efficiency of PSC, such as changing the active layer, insertion of the electron transport layer and the anode buffer layer. Among the several anode buffer layer materials, Poly(3,4-Ethylenedioxythiophene):Poly(styrene sulfonate) (PEDOT:PSS) is widely used as anode buffer layer due to its high transparency in the visible region, high thermal stability and mechanical flexibility. However, PEDOT:PSS suffers a problem of low conductivity and limits the device application.

In this report, we present the preparation of PEDOT:PSS hole transport layer through a secondary doping with flouro compounds such as hexafluoroacetone (HFA) and hexafluoroisoproponal (HIPA) with various concentrations by spin coating technique. High performance of the hole transport layer is attributed to preferential phase segregation of PEDOT:PSS with HFA and HIPA solvent mixture and solvent post treatment method. The improved performance of PSC was dependent on the structure of organic solvents and the concentration of flouro compounds in PEDOT:PSS solution. Using these optimized buffer layer, conjugated polymer solar cells with a Poly[[9-(1-octylnonyl)-9H-carbazole-2,7-diyl]-2,5-thiophenediyl-2,1,3-benzothiadiazole-4,7-diyl-2,5 thiophenediyl] polymer:[6,6]-phenyl-C71-butyric acid methyl esters (PCDTBT:PC71BM) bulk heterojunction have been produced on glass substrate. The obtained results show that PEDOT:PSS optimized with HFA and HIPA organic solvents can be a very promising candidate for transparent anode buffer layer in the low cost organic solar cell devices.

8830-66, Session PWed

Fabrication and characterizations of PBDTTPD: PC71BM bulk heterojunction solar cell using air brush coating method

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Organic solar cells have attracted a significant amount of attention due to the need to develop an inexpensive clean and sustainable renewable energy source. We report on the fabrication of poly((4,8-diethylhexyloxyl) benzo([1,2-b:4,5-b?]dithiophene)-2,6-diyl)-alt-((5-octylthieno[3,4-c] pyrrole-4,6-dione)-1,3-diyl) /[6,6]-phenyl-C71-butyric acid methyl ester blend active layer using airbrush spray coating method in mixed solvents. The parameters such as spraying time, substrate-nozzle distance for the deposition of active layers were analysed. Optical absorption of the active layers was analyzed using UV-visible spectral studies in the wavelength range from 300 to 800 nm. The surface morphology of the active layers deposited with different parameters was examined using Atomic Force Microscopy. The current density-voltage (J-V) characteristics of photovoltaic cells were measured under the illumination of simulated solar light with 100 mW/cm2 (AM 1.5G) by an Oriel 1000 W solar simulator. We also notice that both the bottom-up and top-down approaches have played important roles in advancing our fundamental understanding of this new class of nanostructures. Finally we attempt to look into the future and offer our personal opinions on what the future trends will be in organic solar cell research.

Keywords: Organic photovoltaic device, bulk heterojunction, PBDTTPD, PC71BM

8830-67, Session PWed

Numerical modeling of time-resolved photocurrent in organic small-molecule donor-acceptor composites

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Organic donor-acceptor (D/A) heterojunctions have been a subject of intensive research, due to their potential applications in a wide variety of organic optoelectronic devices. Numerical modeling of processes occurring in organic D/A materials has been pursued in order to understand physics behind charge generation, transport, and recombination, which is important for further development of improved materials. We use a modified drift-diffusion model to numerically simulate time-resolved photocurrents in small-molecule bulk heterojunctions based on high-performance solution-processable functionalized anthradithiophene (ADT) and pentacene (Pn-R-F8) derivatives. (Here R is a side group which determines molecular packing in the solid state including the D/A separation at the D/A interface, without affecting optical and electrochemical properties of molecules themselves.) An ADT derivative was chosen as the donor, and Pn-R-F8 derivatives with various side-groups R served as acceptors. Composites with a fullerene acceptor PCBM were also studied. Thin films were deposited on glass substrates patterned with Au interdigitated electrodes, and the photocurrent under ~500 picosecond pulsed photoexcitation was measured with sub-nanosecond resolution, at various applied voltages. By fitting simulated time-resolved photocurrents to experimental data, we quantified charge photogeneration, mobility, and trapping rates in our D/A composites depending on the acceptor. Multiple relaxation paths occurring after photoexcitation were revealed, in particular: (i) direct photogeneration of free carriers, (ii) formation of donor-based Frenkel exciton, and (iii) formation of the charge transfer exciton state at the D/A interface. The contribution to photocurrent from each path is dependent on voltage, molecular packing, and the D/A separation at the D/A interface.

8830-68, Session PWed

Transparent bifacial dye-sensitized solar cells based on organic counter electrodes and iodine-free electrolyte

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A transparent bifacial dye-sensitize solar cell (DSSC) was developed based on an organic counter electrode (CE) and an iodine-free electrolyte. For the highly uniform and transparent (transmittance > 90%) organic CE, poly(3,4-ethylenedioxythiophene) (PEDOT) film was prepared by electropolymerization of 2,2'-bis(3,4-ethylenedioxythiophene) (bis-EDOT) as the monomer on FTO glass substrate. For the iodine-free electrolyte, an ionic liquid (1, 2-dimethyl-3- propylimidazolium iodide, DMPII) was employed as the charge transfer intermediate without the addition of iodine. Due to the high transparence of the CE and non-absorption character of the iodine-free electrolyte, the bifacial device could not only yield a promising front-illuminated ? of 6.24%, but also produce an attractive ? as high as 4.38% for rear-side irradiation, which exceeds the rear-illuminated ? of 3.96% achieved for the same type of device, fabricated with the dark-colored iodine containing electrolyte. The transmittance of the CE and absorption of the electrolyte were evaluated by UV–vis spectroscopy. The electrocatalytic activity of the organic CE and the charge recombination rate of the devices were investigated by electrochemical impedance spectroscopy (EIS). This bifacial design for DSSCs presents promising prospect for façade applications.

8830-69, Session PWed

Energy level control in D-A conjugated polymers: design and synthesis of new low band gap polymers containing thiophene and cyanovinylene units

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Donor-acceptor (D?A) conjugated polymers have attracted a good deal of attention in recent years. In D?A systems, the introduction of electron

withdrawing groups reduces Eg by lowering the LUMO levels whereas, the introduction of electron donating groups reduces Eg by raising the HOMO levels. Also, conjugated polymers with desired HOMO and LUMO energy levels could be obtained by the proper selection of donor and acceptor units. Because of this reason, D?A conjugated polymers are emerging as promising materials particularly for polymer light emitting diodes (PLEDs) and polymer solar cells (PSCs)

We report the design and synthesis of four new narrow band gap donor-acceptor (D-A) conjugated polymers, PTCNN, PTCNF, PTCNV and PTCNO, containing electron donating 3,4-didodecyloxythiophene and electron accepting cyanovinylene units. The effects of further addition of electron donating and electron withdrawing groups to the repeating unit of a D-A conjugated polymer (PTCNN) on its optical and electrochemical properties are discussed. The studies revealed that the nature of D and A units as well as the extent of alternate D-A structure influences the optical and the electrochemical properties of the polymers. All the polymers are thermally stable up to a temperature of 300 oC under nitrogen atmosphere. The electrochemical studies revealed that the polymers possess low-lying HOMO energy levels and low-lying LUMO energy levels. In the UV-Vis absorption study, the polymer films displayed broad absorption in the wavelength region of 400?700 nm. The polymers exhibited low optical band gaps in the range 1.70 ? 1.77 eV.

8830-70, Session PWed

Insights into electron and hole extraction layers for upright and inverted vacuum-deposited small molecule organic solar cells

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Organic solar cells (OSCs) are studied for their photo-stability in inert atmosphere. Polymer solar cells with a bulk heterojunction (BHJ) of poly(3-hexylthiophene) (P3HT) and phenyl-C61-butyric acid methyl ester (PCBM) are contrasted with small molecule solar cells with a BHJ of metal phthalocyanine and C60-fullerene. A series of extraction layers are examined for their role in OSC performance and stability, including poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS), MoO3 and CF4 plasma treatment hole extraction layers (HELs), as well as LiF and bathocuproine (BCP) electron extraction layers (EELs). The inter-compatibilities of these extraction layers in polymer versus small molecule OSCs are explored. It is shown that the extraction layers commonly used in small molecule OSCs, CF4 plasma treatment and BCP, can be incorporated into polymer OSCs to achieve good performance. However, the commonly used polymer extraction layers, PEDOT:PSS and LiF, are generally less compatible with small molecule solar cells, resulting in either a slight reduction or complete removal of photovoltaic capabilities respectively. Through photo-aging studies, we show that interfacial extraction layers are necessary to avoid contact photo-degradation, which otherwise leads to strong reductions in OSC efficiencies. We also highlight certain extraction layer combinations that result in strong inter-electrode degradation. This inter-electrode degradation is shown to be exclusively due to thermal effects and is attributed to the release of moisture from PEDOT:PSS. The results highlight the need for the development of new extraction layer materials that serve to both enhance OSC efficiency, but are also resilient to light and heat treatments.

8830-71, Session PWed

Monolithic all-solid-state dye-sensitized solar cells

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The high cost of electricity produced by solar cells compared with electricity from other energy sources is an inhibitor to a more widespread adoption of solar energy. Here, a low-cost monolithic all-solid-state dye-sensitized solar cell (DSSC) was developed with a mesoscopic carbon counter electrode (CE). Based on the design of a triple layer structure, the TiO2 working electrode layer, ZrO2 spacer layer and carbon counter electrode (CE) layer are constructed on a single conducting glass substrate by screen-printing. With a vacuum pore-filling technique, solid-state materials such as PEO/PVDF polymer composite, poly(3-hexylthiophene) (P3HT) and spiro-OMeTAD hole transport material (HTM) could be effectively infiltrated into the multilayer thick films to assemble all-solid-state devices. The high surface area and large pore volume favor the penetration of the solid-state electrolyte materials and could reduce the resistance of the interface between CE and solid-state electrolyte. Correspondingly, efficiency up to 3.23% was obtained with polymer composite electrolyte, 2.62% with P3HT and 3.71% with spiro-OMeTAD hole transport material. This design for monolithic DSSC with a carbon CE presents a promising commercial application prospect.

8830-72, Session PWed

OPV novel architectures for enhanced performance

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In practical photovoltaic systems, more than third of the light's energy is lost due to structural inefficiencies; irrespective of the active materials used. In conventional organic photovoltaics, for example, the insertion of light into the active material is very low. The compromise between optical depth and charge drift path reduces the external quantum efficiency. The use of transparent non-ideal electrodes reduces the charge extraction efficiency; in addition to many other shortcomings. In this paper, I propose a new device structure that eliminates most of these defects and almost doubles the practical efficiency limit of OPVs. It takes advantage of the recent advancements in the field of inkjet printing and the ease of handling organic semiconductors. The device eliminates the barriers between the active layer and the sun increasing light insertion into the active material. The new geometry de-couples the optical depth and the charge drift path. It also allows the utilization of better opaque ohmic electrodes that increase charge extraction. In addition, to several other improvements over the conventional OPVs, the new cell can be completely manufactured using only inkjet printing on, virtually, any substrate like wallpaper. The new structure is made flexible enough to assume various material configurations and to accept any number of stacked active layers. In this paper, the structural shortcomings are characterized. Several complex relations such as film thickness versus charge extraction are profoundly explored. The new device's operation and superior performance are illustrated. Also, a brief commercial viability study on the new cell is shown.

8830-73, Session PWed

Multiscale analysis of effect of solvents on the P3HT-PCBM active layer

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Solvents are often used in the active layer formation process in many photonic applications such as organic solar cell, organic led, organic wavelength conversion and photorefractive materials. In this contribution, multiscale modeling and simulation was used to reveal phase separation in P3HT-PCBM at mesoscale level due to attraction-repulsion between different organic functional groups of active ingredient molecules and solvent molecules. Force field parameters for mesoscale calculation were obtained from dynamic mapping of results from molecular dynamic simulations. DFT calculation was used to describe energy changes of active ingredient molecules due to surrounded residual solvent molecules. The simulation results from no solvent, chloroform, dichlorobenzene and chlorobenzene cases indicated that chlorobenzene exhibits strong attraction with fullerene of PCBM and strong repulsion with all the other functional groups, therefore leads to least phase segregation. DFT calculation showed that residual solvent molecules can slightly lower the energy but do not alter the value of band gap.

8830-74, Session PWed

Study on the lifetime prediction of encapsulated organic solar cell under continuously varying environment

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The lifetime of encapsulated organic solar cell under continuously varying environment was predicted based on total amount of permeated water permeated through barrier layers. Previous study (N. Kim et. Al., Solar energy materials & solar cells, Vol. 101, 140-146, 2012) presented the relation between the overall barrier performance and the shelf lifetime of encapsulated organic solar cells experimentally. Based on previous study, the total permeated water vapor through identical barrier layer under continuously varying environment can be calculated and compared to experimental data. For analytical calculation, diffusion and solubility coefficients were experimentally determined using quartz crystal microbalance as well as calculated based on previous experimental data.

8830-75, Session PWed

Study of aging behavior of carbon nanotube doped P3HT:PCBM organic solar cells

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Introduction of various nano-materials in organic solar cells have shown to improve the device performance in terms of efficiency. However, stability and lifetime of organic photovoltaic still remains an issue of concern. We have investigated the effect of different carbon nanotubes on the optical and electrical properties of P3HT:PCBM thin films. These films were first optimized and then used as active layer in solar cells to study the degradation mechanism. Different concentrations of CNTs by wt. %age were added to P3HT:PCBM dissolved in chlorobenzene. Results of UV-Vis absorption spectra, photoluminescence spectroscopy and conductivity measurements showed that the optimum concentration of CNTs is 2%. An increase in absorption and quenching of emission spectra was observed with increase in CNT concentration. Conductivity of the order of 10-5 S/cm2 was achieved with CNT doping. The organic solar cells (ITO/PEDOT:PSS/P3HT:PCBM+CNT/Al) prepared with different concentrations of CNTs also confirmed that the cell with 2% concentration showed the best current-voltage characteristics. The aging behaviour of pristine and doped solar cells was studied in details by various techniques, and it was found that the degradation was lowered by CNT doping, which was compared by efficiency vs. time of the devices. Further, the degradation can be mainly attributed to the changes at the polymer/electrode interfaces.

8830-76, Session PWed

Flexible organic solar cells with integrated grating structures

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In the past years, organic solar cells have gained an increasing amount of attention due to their appealing properties such as mechanical flexibility, low weight, potential low cost and ease of processing. Recently, the power conversion efficiency of both polymer and small molecule solar cells has surpassed 10% and new materials and integration methods are continuously investigated for improving it further. One integration technique that is employed for increasing the solar cell efficiency is introduction of light-trapping structures within the cells, which leads to an enhanced light absorption in the organic thin-films.

In the work presented here, we report on development of flexible polymer solar cells with integrated diffraction gratings on the bottom electrodes. The presented results include P3HT:PCBM and PCPDTBT:PCBM solar cells, fabricated in an inverted geometry, that contains implemented grating structures whose pitch is tuned to match the absorption spectra of the different active layers. This optimized solar cell structure leads to an enhanced absorption in the active layer and thus improved short-circuit currents in the fabricated devices. Fabrication of the solar cells on thin polyimide substrates which are compatible with the lithographically processed grating structures are done in order to obtain the efficiency enhancement in thin, flexible devices.

8830-77, Session PWed

Tin naphthalocyanine complexes for infrared absorption in organic photovoltaic cells

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Typical single-cell bulk heterojunction (BHJ) OPVs are typically limited to an optical absorption within to visible spectrum (350-750nm). However, approximately 50% of the solar photon flux occurs at wavelengths greater than 750 nm. Several different types of materials have been used to extend the absorption in this infrared (IR) region of the solar spectrum. Herein, we investigated the use of Tin naphthalocyanine dichloride (SnNcCl2) as an electron donor material. SnNcCl2 is attractive in this capacity due to its low energy gap which leads to an optical absorption of greater 1100 nm. Simple bilayer devices with C60 as the electron acceptor material demonstrated a power conversion efficiency of 1.2% under simulated AM1.5G solar illumination at 100 mW/cm2. This result was compared with those of similar devices using Tin phthalocyanine (SnPc) as the donor material and it was found that the SnPc devices were dependent on dimer formation within the films for infrared absorption whereas SnNcCl2 owed its IR absorption to its extended conjugation within the molecule. A recent study has shown that Tin naphthalocyanine compounds can be further altered synthetically to tune the absorption characteristics. Consequently, it is expected that SnNcCl2 and materials of its ilk could be used in BHJ solar cells without exclusion of the infrared region.

8830-78, Session PWed

Influence of single regiodefects on the charge transport properties and microstructure of monodisperse, highly regioregular poly(3-hexylthiophene)

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Regioregular poly(3-hexylthiophene) (RR-P3HT) is a hole transporting material widely studied in polymer solar cells and organic field-effect transistors. Much research has been devoted to understanding the relationship between RR-P3HT film microstructure, charge transport behaviour and device operation. Here, aided by the synthesis of monodisperse, highly regioregular P3HT, we are able to systematically study the effect of regiodefects on charge transport and film microstructure. The properties of 'single-defect' RR-P3HT with one single tail-to-tail (TT) defect randomly located within a polymer chain, are compared with defect-free RR-P3HT of comparable molecular weight. Different molecular weights in the 7 kDa – 30 kDa range are studied.

Charge transport is studied via temperature-dependent Time-of-Flight measurements with spatial and energetic disorder parameters calculated within the Gaussian disorder model framework. The microstructure of RR-P3HT films with and without regiodefects is then probed using grazing-incidence wide-angle x-ray scattering (GIWAXS). We also examine the impact of thermal annealing protocols, and finally draw conclusions on the relationship between the presence of regiodefects, the inherent microstructural organisation of bulk RR-P3HT and its charge transport behaviour.

8830-79, Session PWed

Optimization of solution-processed merocyanine BHJ solar cells by the use of solvent mixtures

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The influence of casting from solvent mixtures on the performance of small molecule organic solar cells (SM-OSC) based on merocyanine (MC) dyes is investigated. Blends of the electron acceptor [6,6]-phenyl-C61-butyric acid methyl ester (PC61BM) and the MC dye EL86 have been spin cast from mixtures of chlorobenzene and different common solvents and have been employed in a simple bulk heterojunction setup of ITO/PEDOT:PSS/dye:PC61BM/Al. Solar cells with efficiencies as high as 3.0% could be obtained when using butanol as co-solvent to chlorobenzene. This improvement of 35%—compared to the device cast from pure chlorobenzene—is attributed to a change of the PEDOT:PSS work function. We show by Kelvin Probe measurements that the work function of PEDOT:PSS can be gradually increased up to 360 meV affecting all solar cell characteristics due to a more favorable energy level alignment with the low HOMO energy MC dye EL86. Consequently, the characteristics of OSCs based on other MC dyes could be improved as well. The energy level alignment itself will be subject of further investigations by photoelectron spectroscopy. It is worth mentioning that this effect on solar cell performance can only be observed when the alcohol is added to the spin casting solvent emphasizing the complexity of interface manipulation in solution processed OSCs. Further optimization of the device setup increases the power conversion efficiency of EL86 based devices to 4.0% under simulated AM1.5 illumination of 100 mW cm-2 and to 5.8% at reduced light intensities.

8830-80, Session PWed

Nano-biomaterials based on purple membranes and quantum dots

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The development of photosensitive nano-biomaterials engineered from biomembranes and semiconductor quantum dots (QDs) is a modern field at the interface of biophysics and bionanotechnology. Recent nano-bioengineering approaches employing QDs integrated with bacteriorhodopsin or purple membranes (PMs) permit the enhancement of the light-harvesting capacity of such systems, thus providing a strong impetus to the development of photovoltaic devices.

Here, we demonstrate advanced approaches to engineering of highly organized, oriented films from PMs of Halobacterium salinarum containing the photosensitive protein bacteriorhodopsin. Such ultrathin oriented PM films with QDs, covered with poly(ethylene glycol) (PEG) or cysteine (Cys), may be regarded as prototypes of hybrid nano-biomaterials with photovoltaic, energy transfer, and optical switching properties. Having compared different techniques for obtaining thin films with homogeneity and orderliness sufficient for industrial applications, we have shown that electrophoretic sedimentation provides the best results.

The particular differences of the photopotential parameters for the system PM-QDPEG or PM-QDCys as compared to the "individual" PM films were found. These changes in the photopotential values are correlating with the parameters of the bacteriorhodopsin photocycle that can be important advantage for the further materials application.

The biotechnological approach using site-directed mutagenesis permits fine adjustment of PM biophotovoltaic functionalities, thus enabling the development of hybrid nano-biomaterials with considerably improved functions useful for optical switching and photovoltaic applications.

8830-81, Session PWed

Effects of molecular orientation on the energetics at the donor-acceptor interface and exciton transport in zinc phthalocyanine-based bilayer solar cells

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Variation in molecular orientation in organic solar cells can lead to significant differences in power conversion efficiency. This work analyses how molecular orientation effects both the energetics and recombination rate at the donor-acceptor interface as well as exciton transport in Zinc Phthalocyanine (ZnPc) based bilayer solar cells. A thin 1 nm Copper Iodide layer at the anode was used to induce the change in orientation of the ZnPc molecules in the ZnPc active layer. GIWAXS/NEXAFS characterizations were performed on the ZnPc films to probe the molecular orientation. Devices with copper iodide showed a significantly higher power conversion efficiency (PCE) as compared to those without copper iodide (CuI). Charge Transfer state measurements were performed on ZnPc films and bilayer devices respectively and results show little difference in charge transfer state energies, suggesting marginal contribution of interfacial effects in the difference in performance. Ultraviolet photoelectron spectroscopy was also used to characterize the material and interfacial energetics for both orientations. Overall the results point towards exciton diffusion lengths accounting for most of the difference in PCE's.

8830-82, Session PWed

Optical modeling-based design and evaluation of inverted PTB7:PC71BM photovoltaics

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Further improvement of efficiencies in polymer photovoltaics is needed for commercialization and widespread adoption. Recent progress owes largely to the introduction of new donor materials with wide absorption ranges. Still, means of controlling and enhancing absorption without lowering open circuit voltages are highly desirable. In this work we present computational and experimental results of spectral sculpting enhancement of absorption and control using optical cavity effects. These effects increase absorption over a range of wavelengths that can be controlled simply by varying the bulk heterojunction (BHJ) or other layer thicknesses within the device.

Optical transfer matrix calculations were used to simulate absorption spectra within the BHJ layer. By varying BHJ and ZnO layer thicknesses, optimal and other interesting device architectures were determined. The active layer, a (1.0:1.5 wt) mixture of Poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b']dithiophene-2,6-diyl] [3-fluoro-2-[(2-ethylhexyl)carbonyl] thieno[3,4-b]thiophenediyl]] (PTB7) and [6,6]-phenyl C71 butyric acid methyl-ester (PC71BM) was selected for its large power conversion efficiency and large oscillator strength. Devices were fabricated in an inverted architecture: glass/Indium Tin Oxide (ITO)/ZnO/PTB7:PC71BM/MoO3/Ag to improve device stability and avoid relatively corrosive charge-selective layers. IV-curves and External Quantum Efficiencies (EQE) of cells were measured using a solar simulator (Sol2A, Oriel) and benchtop EQE setup (QEX10, PV Measurements Inc.) and then compared with transfer matrix theory. Strong agreement between simulated absorption spectra and EQE as well as power conversion efficiencies in excess of 7.5% for the optimal devices indicate the sound approach of using optical transfer matrix theory to optimize and shape absorption spectra in polymer photovoltaics.

8830-83, Session PWed

Organic solar cell degradation pathways: qualitative and quantitative imaging analysis

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We report about collaborative efforts on investigating the main degradation mechanisms of state-of-the-art organic small molecule and polymer solar cells by accelerated stability tests in combination with imaging analysis. Solar cells have been degraded under various stress conditions including elevated temperature and illumination under different light sources. Evaluation of devices was done by several imaging techniques such as luminescence imaging, lock-in thermography and light beam induced current, which are complemented by standard IV-characterization. Despite a qualitative interpretation of the different images yielding general knowledge about degradation pathways, quantitative analysis provides valuable additional information. Despite conventional and inverse polymer solar cell architectures, also evaporated organic photovoltaic devices were investigated. As main conclusion, the stability of to-dates organic photovoltaic devices remains dominantly limited by electrode degradation and the quality of the sealing, whereas intrinsic degradation of the organic photoactive layer plays only a minor role. This work provides guidelines for future improvements of stable organic solar cell device operation.

8830-84, Session PWed

Determination of thin film thickness by optical simulation and RBS techniques in flexible organic photovoltaic cells

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This paper gives a computational analysis of thin film thickness using the “Optical” software with refractive index data and results from optical measurements of an Organic Photovoltaic (OPV) with Poly-3-hexylthiophene: [6, 6]-phenyl-C61-butyric acid methyl ester (P3HT:PCBM) as active layer, Polyethylene Terephthalate (PET) as substrate, ITO and Al as electrodes, and Poly (3, 4-ethylenedioxythiophene) Polystyrenesulfonate (PEDOT:PSS) as the hole transport layer. Easier deposition mechanism is employed in this research to fabricate this flexible multilayer structure. Rutherford Back Scattering (RBS) was used to confirm the ITO thickness simulated using the “Optical” Software to be 90 nm as compared to the latter’s ~100 nm result. This research also provides a guideline for mixing P3HT:PCBM which was the active layer used in fabricating the flexible Organic Photovoltaic cell in this research.

8830-85, Session PWed

Extremely strong room temperature transient photocurrent-detected magnetic resonance in organic devices

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An extremely strong room-temperature photocurrent (PC or IPC)-detected magnetic resonance (PCDMR) that elucidates transport and trapping phenomena in organic devices, in particular solar cells, is described. When monitoring the transient PCDMR in ITO/MEH-PPV/Al devices, where the MEH-PPV film was baked overnight at 100 C in O2, it is observed that |delta(IPC)/IPC| peaks at values >> 1, where delta(IPC) is the change in IPC induced by magnetic resonance conditions. Importantly, delta(IPC) and IPC are of different origin. The mechanism most likely responsible for this effect is the spin- dependent formation of spinless bipolarons adjacent to negatively-charged deep traps, apparently induced in particular by oxygen centers, to form trions.

8830-86, Session PWed

Strain evolution of poly(3-hexylthiophene) crystals in a bulk-heterojunction thin film

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In thin film devices, strain is inevitable and is related to the optical and electrical device properties. A comparison of inorganic and small molecule organic systems fabricated via thermal deposition techniques shows that strain in polymer thin films has not been extensively examined because such films are generally fabricated by solution processes. Polymer films that are thinner than the diameter of the unperturbed molecule, fabricated by spin-coating processes, display internal residual stress generated by rapid solvent evaporation.

In this work, we show that poly(3-hexylthiophene) (P3HT) crystals exhibit tensile strain in unannealed P3HT:PCBM blended films. The strain displayed different relaxation behavior during thermal annealing in the absence or presence of an Al electrode layer.

We obtained real-time lattice strain variations in the P3HT crystals via grazing incidence x-ray wide angle scattering measurements using in situ annealing equipment. The strain relaxation properties offered a plausible explanation for the better performance of organic photovoltaic devices based on annealed, as opposed to unannealed, P3HT:PCBM-based thin films. The main effects of annealing in a P3HT:PCBM system were to improve the phase separation of P3HT and PCBM, thereby forming better interpenetrating networks and to enhance the crystallinity of P3HT crystals. However, the enhancement was not prominent in this case. One aspect of the performance improvement is related to Al diffusion, which affects the distribution of P3HT crystals. This work suggests that the strain properties can also explain the improved device performance in the annealed system. The temperature-dependent strain properties depended on the annealing process in the presence and in the absence of an Al layer.

8830-87, Session PWed

Rhenium oxide as an efficient p-dopant to overcome S-shaped current density-voltage curves in organic photovoltaics with a deep highest occupied molecular orbital level donor layer

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One approach to improve the power conversion efficiency (PCE) of organic photovoltaic (OPV) cells is to use a donor with a low highest occupied molecular orbital (HOMO) level to increase the open circuit voltage (VOC) since the VOC is related to the energy gap between the HOMO level of the donor and the lowest unoccupied molecular orbital (LUMO) level of the accepter. However, when they are deposited directly on the indium tin oxide (ITO) anode, a large energy level difference between the workfunction (WF) of ITO and the HOMO level of the donor leads to an S-shaped current density-voltage (J-V) curve, reducing the fill factor (FF) and the PCE.

In this presentation, we inserted a p-doped hole transport layer (p-HTL)/intrinsic hole transport layer (HTL) bilayer between the ITO anode and the donor layer to remove the S-shape in the OPV cell. Effect of p-dopants in a p-HTL inserted between ITO and a donor layer of ?,?'-bis(2,2-dicyanovinyl)-quinquethiophene (DCV5T) with a deep highest occupied molecular orbital level is reported. Among the p-dopants of ReO3, MoO3, WO3 and CuI, ReO3 possesses the largest work function and turns out to be the most efficient p-dopant to remove the S-shape of the current density-voltage curve in the OPV cells. The rest of the dopants could not get rid of the S-shape, even with a doping concentration of 25 mol%. The difference among the dopants can be understood by the different charge generation efficiency of the dopants.

8830-88, Session PWed

Microstructure-dependent photocarrier dynamics in pBTTT:PCBM blends

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The nature of the mixed phase in donor-acceptor bulk heterojunction (BHJ), blends of conjugated polymers and fullerene derivatives, has become an area of intense interest in recent years, particularly with respect to the relationship(s) between the microstructure, photophysical properties and device performance. We use time-correlated single-photon counting (TCSPC) and flash-photolysis time-resolved microwave conductivity (FP-TRMC) to probe exciton generation and dynamics; and carrier generation, transport and decay in a model BHJ system consisting of the thiophene-based conjugated polymer poly(2,5-bis(3-alkyl-thiophene-2-yl)thieno[3,2-b]thiophene)s (pBTTT) blended with the prototypical electron acceptor [6,6]-phenyl-C61-butyric acid methyl ester (PC61BM). We employ molecular additives to control the extent of mixing between the polymer and fullerene derivative, and correlate the photophysics with the induced microstructure. We demonstrate that by controlling the morphology of the intimately mixed phase and the pure polymer and fullerene domains we can influence the dynamics of generation and decay of photoinduced electrons and holes. Finally, we will discuss the results within the context of organic photovoltaic (OPV) device performance.

8830-89, Session PWed

Pore filling of spiro-OMeTAD in solid-state dye-sensitized solar cells determined via optical reflectometry

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A simple strategy is presented to determine the pore-filling fraction of the hole-conductor 2,2-7,7-tetrakis-N,N-di-pmethoxyphenylamine-9,9-spirobifluorene (spiro-OMeTAD) into mesoporous photoanodes in solid-state dye-sensitized solar cells (ss-DSCs). Based on refractive index determination by the film's reflectance spectra and using effective medium approximations the volume fractions of the constituent materials can be extracted, hence the pore-filling fraction quantified. This non-destructive method can be used with complete films and does not require detailed model assumptions. Pore-filling fractions of up to 80% are estimated for optimized solid-state DSC photoanodes, which is higher than that previously estimated by indirect methods. Additionally, transport and recombination lifetimes as a function of the pore-filling fraction are determined using photovoltage and photocurrent decay measurements. While extended electron lifetimes are observed with increasing pore-filling fractions, no trend is found in the transport kinetics. The data suggest that a pore-filling fraction of greater than 60% is necessary to achieve optimized performance in ss-DSCs. This degree of pore-filling is even achieved in 5 ?m thick mesoporous photoanodes. It is concluded that pore-filling is not a limiting factor in the fabrication of "thick" ss-DSCs with spiro-OMeTAD as the hole-conductor.

8830-90, Session PWed

Copper(II) diphenylamine complex as photosensitizer on dye sensitized solar cells (DSSCs)

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Copper(II) diphenylamine complex as photosensitizer on Dye Sensitized Solar Cells (DSSCs) had been investigated. The aim of this research is to find out the respond addition of dye copper(II) diphenylamine complex, addition of oxalate acid and oxalate sodium on FTO/TiO2 thin film to visible light and the effect of various concentration dye copper(II) diphenylamine complex to DSSC performance.

Slip casting method was used to fabricate FTO/TiO2 and FTO/carbon thin film. The result from FTO/TiO2 UV-Vis spectra show no absorption on visible light. Dye solution was synthesized from CuCl2.2H2O with diphenylamine ligands. UV-Vis spectrophotometry was used to identify FTO/TiO2/dye with various concentration, FTO/TiO2/oxalate acid/dye and FTO/TiO2/oxalate sodium/dye. The addition of oxalate acid and oxalate sodium on FTO/TiO2 thin film did not give significant effect. The result FTIR spectra of FTO/TiO2 and FTO/TiO2/dye show new absorption from aril-NH- group at 1315.45 cm-1 and absorption from C-N group at 1166.93 cm-1.

The performance of DSSC was determined by current curve and voltage method using Keithley 2602 A System Source. In this research, DSSCs are able to convert photon energy become electrical energy. The performance of DSSC on concentration 10-2 M and 10-3 M each produce efficiency 4.49x10-4% and 3.41x10-4% by light intensity 1447 Watt/m2 for 2 cm2 active area.

8830-91, Session PWed

Advanced bio-sensitized photovoltaic cells based on oriented purple membranes and conducting polymers

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Purple membranes (PMs) of the bacteria Halobacterium salinarum containing the photosensitive protein bacteriorhodopsin (bR) are promising for the development of bio-sensitized solar cells. PMs are photo-, thermo-, and chemically stable, may be dried or polymerized within the thick films and they have a high dynamic stability. The development of efficient PM-based bio-sensitized cells is a challenging task for fundamental research, nano-bioengineering, and photovoltaics.

We have engineered a solar cell based on thick films of PMs and a conducting mixture of poly(3,4-ethylenedioxythiophene) and poly(styrene sulfonate) polymers. Although bR-based solar cells have been known before, the novel combination of oriented PMs with these polymers, as well as careful selection of technological parameters and electrodes (ITO, Al, or Ni films) has ensured better photocurrent and photovoltage characteristics (0.5 nA, 6 V). Integration of the light-harvesting and energy-converting CdSe nanocrystals has been shown to additionally improve these characteristics. These improvement may be achieved due to (1) the capacity of nanocrystals for harvesting additional energy in the UV and visible regions of the solar spectrum, (2) the use of nanocrystals with diameters (and, hence, fluorescence colours) adjustable so that their fluorescence spectra considerably overlap with the bR absorption spectrum, and (3) advanced nano-bioengineering approaches to controlled coupling of nanocrystals with PMs ensuring a donor–acceptor distance significantly shorter than the Förster radius and efficient FRET to be occurred. The use of integrated energy-harvesting "nano-enhancers" capable of transferring additional energy to PM films and genetically engineered mutant bRs makes bio-sensitized solar cells competitive components of bioinspired photovoltaic devices.

8830-92, Session PWed

Admittance analysis in (PPE-PPV) polymer (AnE-PVstat) light emitting diodes

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Charge storage properties of anthracene-containing poly(p-phenylene-ethynylene)- alt - poly(p-phenylene-vinylene) (PPE-PPV) polymer (AnE-PVstat) light emitting diodes (OLED) devices were investigated through admittance measurement. Beginning of negative capacitance and light output of the device coincided at flat band voltage (1.8 V) or turn-on voltage, which was the difference of energy band gap of polymer and two barrier offsets between metals and polymer. The proposed analytical model, derived for space charge limited region, was successfull to explain the experimental observations of the present OLED device.

8830-93, Session PWed

Layer-by-layer all transfer based bulk-heterojunction solar cells with interfacial modification

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A novel cost- and time-effective vacuum free process to fabricate bulk-heterojunction (BHJ) organic photovoltaics (OPVs) via layer-by-layer selective stamping-transfer of all layers is described. By controlling the surface properties of polyurethane acrylate (PUA) stamping molds with UV-ozone exposure, PEDOT:PSS, BHJ layer and metal cathode were uniformly transferred layer by layer onto each of the bottom layers. Among several interfaces between each layer, we found that the interface between the active layer and metal cathode is a critical factor in obtaining conventional device like efficiency. To enhance the interfacial connectivity between the BHJ layer and metal cathode, titanium oxide (TiOx) interlayer was introduced. Cell performance was optimized by controlling the concentration of TiOx solution. The P3HT:PC60BM BHJ device fabricated by transferring PEDOT:PSS, TiOx /Active layer, and Al cathode showed 2.01% and the PTB7:PC70BM BHJ device fabricated by transferring TiOx and Al cathode showed 3.76% power conversion efficiency. This efficiency is not comparable with those of conventional OPVs, but our approach shows the possibility of fabricating OPVs via the layer-by-layer transfer method for the first time.

8830-94, Session PWed

Methylammonium lead iodide perovskites/ fullerene planar-heterojunction hybrid solar cells

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We report the fabrication of all-solid-state, methylammonium lead iodide (CH3NH3PbI3) perovskites/fullerene (C60), donor/acceptor planar-heterojunction (PHJ), hybrid solar cells. Spin-casting the ?-butyrolactone solution of methyl ammonium iodide and lead iodide forms a thin CH3NH3PbI3 perovskite film (20~30 nm) on the substrate. The deposition of a thin C60 (acceptor) layer in vacuum on CH3NH3PbI3 perovskite (donor) creates a hybrid PHJ for fabricating solar cells. CH3NH3PbI3 perovskite harvests the wide range of light from visible-to-near infrared and transports the positive charges. No additional hole-transport layer and mesoporous metal-oxide nanostructures for CH3NH3PbI3 perovskite are applied. The CH3NH3PbI3/C60 PHJ devices exhibits the promising photovoltaic performance of open-circuit voltage VOC = 0.55 V, short-circuit current JSC = 5.21 mA/cm2, fill factor FF = 0.57, corresponding to a power conversion efficiency (PCE) of 1.6% under standard 1 Sun AM 1.5 simulated solar irradiation. In addition, the magnitudes of VOC and PCE elevate to 0.65 and 0.75 V, 2.4 and 2.1 % using [6,6]-phenyl C61-butyric acid methyl ester (PCBM) and indene-C60 bisadduct (ICBA), respectively, whose lowest unoccupied molecular orbital (LUMO) level are higher comparing with C60 as the acceptor. These results suggest photovoltaic parameters of CH3NH3PbI3 perovskite/C60 or C60 derivatives PHJ are controlled by the level position offset of donor and acceptor. By the judicious selection of solvent (dimethylformaide) and deposition procedure for preapring CH3NH3PbI3 perovskite film, the hybrid device delivers a 3.0 % PCE with impressive 9.02 mA/cm2 in JSC. Our findings demonstrate the design rules and the possible development of newly structured, hybrid, efficient solar cells.

8830-95, Session PWed

Transferable graphene oxide of electron-transport layer for efficient bulk-heterojunction solar cells by stamping nanotechnology

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Transferable graphene oxide (GO) serves as an electron transport layer (ETL) in bulk heterojuction solar cells. The GO is inserted by stamping nanotechnology, with the help of a transfer film, on poly[N-9"-heptadecanyl-2,7-carbazole-alt-5,5-(4',7'-di-2-thienyl-2',1',3'-benzothiadiazole)] (PCDTBT):[6,6]-phenyl C71 butyric acid methyl-ester (PC71BM). The BHJ solar cells with the GO ETL exhibits improved short circuit current, JSC, and improved Power Conversion Efficiency, PCE, because of efficient electron transport from the BHJ layer to the Al cathode resulting in decreased series resistance and better charge

extraction compared to the device without GO layer. Moreover, solar cells with sequentially coated GO/titanium oxide (TiOx) ETL show a synergistic effect of increased electric field amplitude as inferred from optical simulation. Addition of the GO/titanium oxide (TiOx) ETL leads to the highest PCE of 7.5 %. The BHJ solar cells with GO ETL also exhibit long-term stability, comparable to that of TiOx. BHJ solar cells fabricated with the GO layer inserted by stamping transfer are promising as candidates for high performance devices because of the newly designed ETL which serves to reduce the electronic charge barrier.

8830-96, Session PWed

Ring-protected small molecules for organic photovoltaics

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Recently, excellent solar cell device performances have been achieved with solution-processed small-molecule donor materials. Small molecules have well defined structures and thus allow better control of self-assembly in the solid state. However, the easy formation of H-type aggregates and lack of strong interactions between nanodomains could limit charge transport, device performance, and long-term stability. We have recently explored the synthesis of ring-protected small molecules (with rings surrounding the center of the molecules), studied the intermolecular interactions in solution and solid state, and conducted preliminary solar cell device fabrications. It has been found that the molecules behave very differently from conventional flat small molecules in both solution and solid states. Proton NMR study of solutions of different concentrations revealed the presence of strong intermolecular interactions as a result of absence or shortage of open-ended alkyl side chains; however, such strong interactions do not lead to precipitation of the molecules even at high concentrations. Excellent films are routinely obtained from the neat small molecules despite the much reduced number of solubilizing groups. The New findings strongly suggest that ring protection is an effective strategy to avoid H-aggregation and maintain strong pi-pi interactions simultaneously. Such materials are expected to form head-tail self-assemblies that will embrace the advantages of both small molecules and polymers. More interestingly, thin films of such materials are potentially more isotropic in charge transport than conventional small molecule and polymer films, a property desirable for photovoltaics and some other optoelectronic applications.

8830-97, Session PWed

Benzo[1,2-b:4,5-b]dithiophene- and bithiophene-based ring-protected molecules for photovotaics

Lianjie Zhang, Jianyuan Sun, Logan P. Sanow, Cheng Zhang, South Dakota State Univ. (United States)

Solution-processable small-molecule donor materials have been intensively investigated for photovoltaic application. Small molecules have well-defined structures and thus allow facile self-assembly in the solid state. Various electron-withdrawing groups can be easily incorporated to tune energy gap and intermolecular interactions. Despite these advantages, self-assembly of small molecules in the solid state in principle produces more domain boundaries than polymeric materials and there is a lack of mechanism to connect the nanodomains to prevent hem from physically separating from each other. The intrinsic higher tendency for crystallization and higher molecular mobility may lead to continuous growth of nanodomains into micro crystallites. This could limit charge transport, device performance, and long-term stability. We have recently explored the synthesis of ring-protected small molecules (with rings surrounding the center of the molecules) based on widely used aromatic units such as benzo[1,2-b:4,5-b]dithiophene- and bithiophene, and investigated their potentials for photovoltaic application. With the presence of a ring to prevent molecules from forming H-aggregates, the amount of side chains can be reduced by 80% to allow strong pi-pi interaction to happen as revealed in NMR study in a likely head-tail fashion without causing any problem in solubility and film formation. It appears that that ring protection is an effective strategy to avoid H-aggregation and maintain strong pi-pi interactions simultaneously. Such materials are expected to self-assemble in a way that is different from both conventional small molecules and polymers, and likely form films that are more isotropic in charge transport than usual (self-assembled) organic materials.

8830-98, Session PWed

Microscopic effects of an intermediate exciton blocking layer on the opto-electronic properties of diindenoperylene/C60 bilayer photovoltaic cells

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Interface effects play a dominant role in the performance of organic thin film devices. In the present case, we have analyzed molecular bilayer photovoltaic cells composed of the electron donor (D) Diindenoperylene (DIP) in combination with the electron acceptor (A) C60. These planar heterojunction cells have demonstrated overall efficiencies of up to 4 % [1]. Besides the rather poor absorption of the crystalline DIP layer due to its unfavorable orientation of transition dipoles with respect to the incident light, major limitations are imposed by exciton and charge carrier losses at the cathode interface. We address these questions by variations of the growth conditions and by the implementation of a Bathophenanthroline (BPhen) exciton blocking layer (EBL) between C60 and metal cathode. Complementary measurements of current density, external quantum efficiency, and photoluminescence quenching provide a detailed microscopic picture of the contributing loss processes. The experimental data obtained upon variation of the intermediate BPhen layer thickness between 0nm and 50nm indicated that Ag atoms of the top contact are able to penetrate the whole 35nm thick C60 film leading to exciton quenching already at the D/A interface if no blocking layer is applied. In contrast, for a 5nm thick BPhen EBL an optimal trade-off between exciton blocking, suppression of metal penetration and electron transport has been achieved, improving the overall device efficiency by a factor of two [2].

[1] A. Opitz, et al., IEEE J. Sel. Top. Quant. El. 16, 1707 (2010).

[2] A. Steindamm, et al., Appl. Phys. Lett. 101, 143302 (2012).

8830-99, Session PWed

Hybrid cascade hole extraction layer composed of tungsten oxide/PEDOT:PSS to enhance long-term stability and power conversion efficiency of polymer solar cells

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In recent years, alternatives to poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), which is used polymer solar cells (PSCs), have been actively researched because of its disadvantages such as hygroscopic and acid characteristics in terms of device stability. In order to address this problem, various solution-processable metal-oxide hole extraction layers (WOx, NiOx, MoOx) are studied as an alternative to PEDOT:PSS. However, there are still some problems to be addressed before metal oxides can replace PEDOT:PSS layers such as difficulty to control the work function of metal oxide films easiliy for applying to all donor polymers with different HOMO levels and low inital power conversion efficiency compared to devices with PEDOT:PSS.

Furthermore, PEDOT:PSS is still an attractive material due to its many advantages compared to metal oxides, such as good conductivity, low-temperature solution processability and proper work function that is well-matched with the HOMO energy levels of most donor polymers.

In this study, PSC devices are fabricated with a hybrid hole extraction layer (H-HEL) composed of tungsten oxide and PEDOT:PSS layers in order to determine the synergistic effects of hybridization. As a result, the device with a H-HEL showes better long-term stability in both P3HT:PC60BM and PTB7:PC70BM BHJ systems because the ultra-thin oxide layer effectively blocked indium diffusion from the etched ITO glass. In additon, power conversion efficiency of the device is slightly improved in two different P3HT:PC60BM and PTB7:PC70BM systems due to the increased JSC, which was caused by efficient hole extraction from the cascade energy level alignment of the H-HEL.

8830-100, Session PWed

Surface modification of Al-doped ZnO transparent electrodes for efficient carrier collection in organic solar cells

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The work function difference between electrodes is one of the crucial parameters that determine the performance or various organic electronic devices including organic solar cells. Aluminum-doped zinc oxide (AZO) films have lower work function comparing to indium tin oxide (ITO), which promotes their use as transparent electrodes in inverted organic solar cell devices. Additionally, by introducing magnesium into AZO films, a decrease of the conduction band minimum with respect to the vacuum level can be achieved. It enables an effective work function adjustment to an adjacent organic layer, which, in turn, can enhance the photogenerated and extracted charge carrier collection efficiency.

In this work, we applied atomic layer deposition (ALD) to grow AZO films with a very thin (a few nanometers) Zn1-xMgxO:Al layer grown on the top of the AZO film. The advantage of the ALD technique is its ability to grow very conformal films with the thicknesses controlled in the nanometer-scale. By changing the Mg content from $x = 0$ to $x = 0.4$, we observed the respective decrease of the work function of the films which resulted in the increase of the rectification properties of the organic single layer structures. We also show the influence of AZO transparent electrodes with Mg surface modification on the photovoltaic efficiencies of the test structures.

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8830-101, Session PWed

Organic solar cells with Au-Ag nanowire electrode

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In an attempt to overcome the limitations of the presently prevailing transparent conducting electrode (TCE) – indium tin oxide (ITO) – many materials have been considered for replacing ITO. Recently, a novel method has been reported for the synthesis of Au-Ag NW mesh, and tested successfully for organic-light-emitting-diodes (OLEDs). It employs UV-induced reduction of gold- and silver- precursors to form Ag-Au Nanowire mesh. In this report, Ag-Au Nanowire mesh are formed on glass plate and employed as transparent anode for organic-solar-cell fabrication. The electrode showed good transparency and reasonable sheet resistance. The advantage of the technique is its simple processing method and cost-effectiveness.

8830-102, Session PWed

Review: novel silver nanowire mesh for transparent conducting electrode

Siddhartha Saggar, Predeep Padmanabhan, National Institute of Technology Calicut (India)

The purpose of this paper is to explain about a novel material for transparent conducting electrode (TCE) – mesh of silver nanowires (AgNW) – for organic optoelectronic application. With the transmission normalized over an area of the opening observed to be more than 100%, these materials have shown transmitivity higher than 90%, which is competitive with the conventionally used transparent conducting electrode – indium tin oxide (ITO). With good transparency and reasonably lower sheet resistance, these AgNW TCEs offer hope to various problems related to ITO use in such devices. In the article, various techniques of AgNW electrode fabrication are analyzed and comparative features are also provided.

8830-103, Session PWed

Alkyl chain modification leading to enhanced OPV device performance in thieno[3,2-b] thiophene-diketopyrrolopyrole based polymers

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Diketopyrrolopyrrole (DPP) unit was developed over four decades ago for high performance pigments. Owing to its strong absorption in the visible region and electron withdrawing nature it became a promising building block for small band gap conjugated polymers. When polymerized with electron-donating monomers, the resulting polymers show energy band gaps smaller than 1.5 eV. In recent years, there has been an intensive effort to develop polymers based on the DPP unit for photovoltaic applications; PCEs over 6% have been reported.

Recently, we have reported Thieno[3,2-b]thiophene-diketopyrrolopyrole (DPPTT-T) based polymers which led to PCEs of about 5.5%. To further tune optoelectronic properties of these polymers, we decided to alter the branching position of the solubilising chain on the DPP core. Moving the branching point away from DPP core, we were able to achieve high performing solar cells. Initial device performance of these polymers was above 7%. In depth studies of device performance in single junction devices, inverted and tandem solar cells will be presented.

8830-104, Session PWed

Performance improvement of dye-sensitized solar cells by surface patterning of FTO electrodes

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Patterned FTO electrodes for dye-sensitized solar cells (DSSCs) are fabricated by a facile wet etching method. The pattern depth can be controlled by altering etching time. FTO is thoroughly etched away when etching time is over 300s. Most DSSCs with patterned FTO electrodes exhibit both larger open-circuit voltage (Voc) and short-circuit photocurrent density (Jsc) as compared to the DSSC with unpatterned FTO electrode. The energy conversion efficiency of DSSC (n) gradually increases with increasing etching time and achieves a highest value when etching time is 240s. Then it drops abruptly as etching duration is longer than 240s. This indicates that an optimum pattern depth approximately 190 nm is required to acquire the best DSSC performance. The improved performance can be mainly attributed to enhanced light harvesting and light scattering due to larger amount of TiO_2 nanoparticles filled in the pattern and more dye adsorption. More contact between TiO_2

nanoparticles and patterned FTO with larger surface area is also an advantage. The sheet resistance of FTO dramatically increases when etching time is over 240s, and this can explain why device efficiency starts to reduce. It has been revealed from Nyquist plots that the charge transfer impedance at the TiO2/dye/electrolyte interface apparently influences the magnitude of Jsc as well as device performance. Electron transfer becomes easier and a higher n is thereby obtained when a DSSC has a smaller interfacial impedance. This study has demonstrated that there is obvious improvement in DSSC performance by surface patterning of FTO electrodes. With an appropriate etching condition, the highest n of 6.76% can be achieved, which is around 17% higher than that of the DSSC with unpatterned FTO electrode.

8830-31, Session 7

Charge generation and recombination in high open circuit voltage organic solar cells *(Invited Paper)*

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We demonstrate that modern high-performance organic photovoltaic (OPV) devices designed for solar energy conversion sometimes exhibit properties that appear to transcend historic design rules. We believe the reason for this lies in a balance between thermodynamic and kinetic factors that work together to control charge generation and recombination efficiency. For example, we find that the internal quantum efficiencies of photocurrent generation in poly(indacenodithiophene-co-phenanthro[9,10-b]quinoxaline):fullerene devices approach 100% despite the energy of the interfacial charge transfer state formed between the electron donor and the electron acceptor being higher than the energy of the donor triplet exciton in this blend. These results suggest that the kinetics of charge separation in well-optimized systems can outcompete charge recombination via the donor triplet, a process previously thought to limit photocurrent collection in high voltage devices. We define general features in the energy landscape that we believe to be critical for efficient photocurrent generation. We use a suite of spectroscopic techniques to identify new strategies for materials design aimed at controlling the kinetics of charge generation and recombination in these devices. We discuss the implications of our results for future device optimization by rational design.

8830-32, Session 7

Engineering energy transfer and exciton diffusion in organic semiconductors for application in photovoltaic cells

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Organic photovoltaic cells (OPVs) rely on the efficient dissociation of photogenerated excitons. In simple planar heterojunction OPVs, this dissociation occurs at an electron donor-acceptor interface, requiring the exciton to diffuse from the point of photogeneration in order to be harvested. This need for efficient exciton migration limits the performance of these cells, a limitation that is typically addressed through the use of bulk heterojunctions. We present an alternate approach that directly engineers the characteristic exciton diffusion length (LD) by optimizing the intermolecular separation and consequently, the photophysical parameters responsible for excitonic energy transfer. By diluting the electron donor boron subphthalocyanine chloride into a wide-energy-gap host, we optimize the degree of interaction between donor molecules and observe a ~50% increase in LD. The measured increase in LD is well-predicted using F?rster theory and separate measurements of material photophysics. Using this dilute-donor approach, we demonstrate planar heterojunction OPVs with a power conversion efficiency of 4.4%, >30% larger than optimized devices containing an undiluted donor layer. Interestingly, we have found that similar behavior is also observed in undiluted rubrene derivatives with a varying degree of steric bulk and hence also intermolecular separation. The dependence of LD on the intermolecular separation is again well-predicted using F?rster theory. In both of these cases, the clear correlation between LD and the degree of intermolecular interaction has broad implications for the design of OPV active materials and device architectures.

8830-33, Session 7

Energy level alignment and sub-bandgap charge generation in polymer:fullerene bulk heterojunction solar cells

Sai-Wing Tsang, Song Chen, Franky So, Univ. of Florida (United States)

Polymer solar cells with power conversion efficiencies (PCEs) over 8% have been demonstrated in laboratories with advances of novel materials, device processing, and device architectures. However, some critical physical properties of the polymer:fullerene bulk heterojunctions (BHJs) such as the donor-acceptor interface energetics which controls the charge transfer process are not well understood. In a BHJ photovoltaic cell, the open-circuit voltage (VOC) is determined by the energy level difference of the highest-occupied-molecular-orbital (HOMO) of the donor and the lowest-unoccupied-molecular orbital (LUMO) of the acceptor. However, there is lack of experimental approach to directly probe such alignment in a working device.

In this presentation, we will demonstrate a technique—charge modulated electroabsorption spectroscopy (CMEAS) to directly determine the effective bandgap and the interface effective force in a polymer:fullerene BHJ system.[1] By measuring the electroabsorption (EA) signal due to charge-modulation (CM) in the polymer, we are able to observe a clear sub-bandgap signal through direct excitation of excitons to the charge transfer states. Such a differential spectrum measured by CMEAS has a much higher signal-to-noise ratio than that measured by linear optical absorption techniques. Compared to the conventional electrochemical method, CMEAS can probe the energy level alignment at the electron donor-acceptor interface in a working BHJ photovltaic cell. Using CMEAS, for the first time we are able to directly probe the effective bandgap in polymer:fullerene systems. The results also bring insight into the details of the charge transfer states and the origin of VOC in polymer photovoltaic cells.

[1] Sai-Wing Tsang, Song Chen, and Franky So, Adv. Mater. 2013 (in press)

8830-34, Session 7

Charge transport and recombination in organic bulk-heterojunction materials in the in-plane direction *(Invited Paper)*

Ananth Dodabalapur, David A. Vanden Bout, Christopher J. Lombardo, Micah Glaz, Zien Ooi, Marlene Gutierrez, Oleksiy Slobodyan, Eric Danielson, The Univ. of Texas at Austin (United States)

Effective characterization of charge transport and recombination parameters in bulk heterojunction (BHJ) materials used in organic photovoltaic cells (OPV) is of vital importance for understanding how to increase the power conversion efficiency of these devices. These parameters, such as carrier mobility, carrier concentration, and the recombination coefficient have traditionally been successfully measured using vertical structures similar to OPV devices. Carrier mobility can be anisotropic in BHJ systems, particularly those used in high efficiency solar cells. We propose to characterize organic BHJ materials along multiple axes to measure the directional dependency of mobility and

measure isotropic parameters such as carrier concentrations and the recombination coefficient to obtain a more complete picture of charge transport within these materials. We have developed a lateral BHJ device which complements information that can be obtained from vertical structures by allowing the measurement of electrical properties along the transport direction of charge carriers. We employ several diagnostic methods with the lateral structures. One method involves the fabrication of several closely spaced voltage probes (fabricated by electron beam lithography) to perform in-situ potentiometry which yield valuable information about the recombination mechanisms and coefficient. The second method is based on scanning photocurrent microscopy which also yields information about the extent of the space charge layers from which several parameters can be extracted. We also present a numerical model to quantitatively understand and predict material properties from these lateral device measurements.

8830-35, Session 7

Molecular structure-dependent electron transport in fullerene acceptors for organic photovoltaics

Andrew J. Ferguson, Alex Nardes, Nikos Kopidakis, National Renewable Energy Lab. (United States)

The donor-acceptor bulk heterojunction (BHJ), blends of conjugated polymers and fullerene derivatives, has become the dominant and best-performing microstructure in organic photovoltaic (OPV) devices. In recent years sophisticated structural studies have identified a previously undetected phase consisting of intimately mixed polymer and fullerene molecules, although the importance of this phase to the photophysical and electrical performance of these systems is still a matter of debate. Furthermore, the rapidly advancing development of new high performance conjugated copolymers necessitates the design and synthesis of novel fullerenes with wider tenability than the available materials today. We use flash-photolysis time-resolved microwave conductivity (FP-TRMC), in conjunction with other spectroscopic and device-based techniques, to probe carrier generation, transport and decay in BHJs of various conjugated polymers and fullerene derivatives in an effort to address a) the importance of mixed polymer-fullerene phases and b) the electronic properties of new fullerene derivatives. We demonstrate that electron transport in the fullerene phase is dependent on both the molecular structure and fullerene domain size within the conjugated polymer “host”. We also explore the mixing of fullerene derivatives in both ordered and disordered polymer domains, and propose a mechanism for electron transport in these domains that correlates to the operation of organic photovoltaic devices.

8830-36, Session 7

Empirically based device modeling of bulk heterojunction organic photovoltaics

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We developed an empirically based optoelectronic model to accurately simulate organic photovoltaic (OPV) devices with novel materials. Bulk heterojunction (BHJ) OPV devices based on a new low band gap dithienothiophene-DPP donor polymer, P(TBT-DPP), is blended with PC70BM for various donor-acceptor weight ratios and solvent compositions. Photovoltaic devices produce power conversion efficiencies ranging from 1.8% to 4.8% at AM 1.5G. The mobilities of electrons and holes are determined using space charge limited current. Bimolecular recombination coefficients are both analytically calculated using slowest-carrier limited Langevin recombination and measured using an optical pump-probe technique. Exciton quenching efficiencies in the donor and acceptor domains are determined from photoluminescence spectroscopy. In addition dielectric and optical constants are experimentally determined. The simulation results using these physically measured parameters yield calculated photocurrent as a function of applied bias with less than 7% error for all devices. Free carrier generation and recombination rates of the photocurrent are modeled as a function of position in the active layer at various applied biases. These results show that while free carrier generation is maximized in the center of the device, free carrier recombination is most dominant near the electrodes even in high performance devices. Such knowledge of carrier activity is essential for the optimization of the active layer by enhancing light trapping while minimizing recombination. Our simulation program is intended to be freely distributed as a tool in laboratories fabricating OPV devices.

8830-37, Session 8

Optimization of low band gap polymer photovoltaics through structure modification and device engineering *(Invited Paper)*

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For bulk heterojunction (BHJ) photovoltaic devices to realize commercial applications, effective strategies to maximize the performance have to be developed and fundamentally understood. In BHJ-type solar cells, the ability to control and optimize the active layer morphology is a critical issue to improve device efficiency, and this is usually achieved by optimizing the processing conditions, eg. using varied annealing procedures and choosing the right solvent additive. A family of structurally similar low band gap polymers were synthesized where their absorption can be tuned by the choice of monomer units. The morphology of these materials, and their blends with phenyl-C71-butyric acid methyl ester (PCBM) were characterized using x-ray scattering and electron microscopy methods. We observed that by using solvent additive, the morphology could be tuned to produce an interconnected polymer fibril network throughout the film. Details of this morphology, e.g. the inter-fibrillar distance and fibril dimensions are strongly affected by slight chemical structure modifications of the polymer. The best performance comes from the morphology with smaller fibril diameter and inter-fibrillar distance, which can only be obtained by combined processing and structural optimization. Using the conventional binary mixture approach for OPVs, these polymers (deep wavelength absorption) were mixed with short wavelength absorption conjugated polymer and further mixed with PCBM to form ternary blends to enhance the absorption. An enhancement in the device performance was observed and the multi-component thin film morphology was also characterized in detail.

8830-38, Session 8

Probing film structure in organic photovoltaic devices with neutrons

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The structure of the active film plays an important role in controlling the optoelectronic and device properties of organic solar cells. Neutron techniques such as neutron reflectometry (NR) and small angle neutron scattering are important methods for studying physical structures of (macro)molecules and their interactions non-destructively in solution and/or the solid state. In this presentation we will describe results from a time resolved NR measurement that enables the evolution of film structure to be followed. The polymer/fullerene films are generally produced by sequential deposition of the polymer followed by the fullerene, with a subsequent anneal. The structure of the films is then correlated to device performance.

8830-39, Session 8

The impact of polymer molecular weight and the degree of polymer-fullerene mixing on the performance of bulk heterojunction solar cells

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The relationship between polymer-fullerene bulk heterojunction (BHJ) morphology and solar cell performance is complex because both the composition and volume of each phase present in the BHJ play a role in determining device efficiency. Recent reports have shown that fullerene derivatives mix at the molecular level with conjugated polymers, but the role of the composition of the molecularly-mixed phase in these BHJ devices is not well understood. By tuning the composition of the molecularly-mixed phase in BHJ solar cells composed of the polymer PBDTTPD and PCBM, we find that 90% internal quantum efficiency is only attained if the concentration of PCBM mixed with PBDTTPD is above the percolation threshold needed for electron transport. If the concentration of PCBM mixed with PBDTTPD is too low, isolated PCBM molecules act as morphological electron traps and inhibit charge extraction from these BHJs. We also examine the effect of PBDTTPD molecular weight (MW) on BHJ morphology and solar cell performance and find that increasing the MW of PBDTTPD from 23 kDa to 39 kDa improves solar cell power conversion efficiency (PCE) from 4.0% to 7.9%. By thoroughly studying this effect, we elucidate that high MW PBDTTPD aggregates in solution, which leads to an increased degree of crystallinity in BHJs made with high MW PBDTTPD compared to those made with low MW PBDTTPD. This study highlights that both the composition of the molecularly-mixed phase and the degree of polymer crystallinity have drastic effects on BHJ solar cell performance.

8830-40, Session 8

Domain size, purity, and molecular orientation: critical parameters from soft x-ray scattering *(Invited Paper)*

Harald W. Ade, North Carolina State Univ. (United States)

Domain purity and interface structure are known to be critical for fullerene based bulk heterojunction solar cells, yet have been very difficult to study previously due to a paucity of characterization methods. Using novel soft X-ray tools, quantitative measurements of the domain purity and size, and a qualitative characterization of the nature of the structure of the donor/acceptor heterojunction (diffuse, sharp, interdiffused) can be achieved. Furthermore polarized x-ray scattering can reveal preferential orientation of the donor polymer (edge-on or face-on) relative to the bulk heterojunction interface. Such ordering has previously not been observed in fullerene-based solar cells and is shown here to be a critical factor for high performance.

8830-41, Session 8

Understanding the morphology and photophysics of PTB7 bulk heterojunction solar cells

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An important challenge in organic solar cells is to relate the photophysics and morphology to device operation in order to guide the development of improved materials. We have investigated this issue in the highly efficient polymer-fullerene (PTB7:PC71BM) blends. We present a comprehensive study of nanoscale phase separation, exciton dissociation dynamics into charge carriers and device, as well as a measurement of the exciton diffusion length in PC71BM. We find that in blends spin-coated from a solution without additives the fullerene molecules are segregated into pure 20-60 nm clusters which together form ~150 nm fullerene-rich domains. In these blends fullerene exciton dissociation into charge pairs occurs with an efficiency of 90%, yet the solar cell quantum efficiency (IQE) is only 40%, indicating that just 45% of charges are extracted. In contrast, blends spin-coated from a solution with a high boiling point additive form fibre-shaped alternating fullerene and polymer-rich domains which are <40 nm wide and 100-300 nm long in which fullerene excitons dissociate into charge pairs with an efficiency of 98%, with the device IQE reaching 80%. Our results indicate that charge extraction efficiencies with the additive is twice higher than without , and so we conclude that fibre-shaped phase domains are highly beneficial for OPVs because they give efficient charge extraction and minimise recombination.

8830-42, Session 8

In-situ x-ray scattering of solution-printed organic bulk heterojunction (BHJ) solar cells

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Organic bulk heterojunction (BHJ) solar cells consist of a blend of an electron-donating polymer and an electron-accepting fullerene, which form an interconnected network of three phases: a pure polymer, a pure fullerene, and a mixed fullerene-polymer phase. The performance of organic BHJ solar cells is, among other factors, highly dependent on the film morphology, such as molecular packing and the size of the respective phases. It is, therefore, not only crucial to understand how processing parameters influence the final film morphology, but also to gain a deeper understanding of the underlying physics of film formation.

In this contribution, we use synchrotron grazing-incidence small- and wide-angle x-ray scattering (GISAXS and GIWAXS) to study thin films of doctor-bladed organic BHJ's. We show how the molecular packing and phase separation can be controlled by the doctor-blading parameters (e.g., printing speed, solution concentration, solvent). To study the dynamics of BHJ film formation, we have developed a compact and portable doctor-blading setup for in-situ grazing-incidence x-ray diffraction (GIXD). The setup was used to monitor BHJ film morphology evolution, yielding in-situ GIXD data with a time resolution as high 0.3 s.

8830-43, Session 9

Light absorbing donor semiconducting polymers for organic solar cells *(Invited Paper)*

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Understanding the impact of both the organic semiconductor design and processing conditions, on both molecular conformation and thin film microstructure has been demonstrated to be essential in achieving the required optical and electrical properties to enable high efficiency organic solar cell bulk heterojunction devices fabricated from solution. Organic solar cell efficiencies are currently increasing rapidly based on organic bulk heterojunction devices fabricated from solution. Central to these device efficiency improvements are the development of new photoactive semiconducting donor and acceptor materials, designed at the molecular level to optimise both absorption of the long wavelength region of the solar spectrum and generation of high cell voltages. This presentation will examine some of the key design strategies to control the molecular orbital energy levels and microstructure of donor polymer semiconductors and illustrate with examples and their characterisation. Specifically, the systematic modification of the bandgap in a series of bridged ladder type indenofluorene copolymers through tuning molecular orbital energies with atom substitutions in the bridge position, will be illustrated. The impact of lowering the HOMO energy level on cell Voc, and the dependence of the Jsc on bandgap and morphology will be demonstrated.

8830-44, Session 9

Tailor-made absorber polymers for OPV: from synthesis to formulation development *(Invited Paper)*

Silvia Janietz, Alexander Lange, Eileen Katholing, Fraunhofer-Institut für Angewandte Polymerforschung (Germany); Wolfram Schindler, Helmholtz-Zenzrum Berlin für Materialien und Energie GmbH (Germany)

The introduction of adequate donor and acceptor units led to lower polymer HOMO energies for enhanced open circuit voltage in blends with PC70BM). In parallel, the copolymer band-gap was continuously reduced to improve matching of the polymer absorption with the sun spectrum, resulting in higher short circuit currents. Fluorene based terpolymers with different content of dialkyl substituted diphenyl-benzopyrazine or diphenyl-thienopyrazine and triphenylamine units (MR) were synthesized by Suzuki polymerization. The introduction of dialkyl substituted diphenyl-benzopyrazine for example in the fluorene main chain leads to LUMO-energy level of 3.1eV and in solar cells to an open circuit voltage of 0.96 V. Organic solar cells were prepared with inkjet printed consisting of the novel absorber polymer blended with PC61BM in a ratio of 1:2. Different solvent systems were used. It was found that devices prepared from the chlorine-free system showed only slightly lower efficiencies with respect to the chlorinated system, 2.5 as compared to 3.5%, respectively. Another synthetic concept includes the exchange of the fluorine unit through cyclopentadithiophene units in to the main chain to shift the absorption more in the IR. As the acceptor unit were chosen benzothiadiazole or fluorinated benzothiadiazole. Stille microwave coupling reaction was used for the synthesis of these polymers. Due to the strong impact of molecular weight on solar cell performance both polymers were synthesized with equivalent Mw and compared in blends with PC70BM.The exchange of the hydrogen against an flour atom on the benzothidiazole ring in the polymer chain causes the PCE to increase from 3,6 to 6,5 %.

8830-45, Session 9

Ionic high-performance light harvesting and carrier transporting OPV materials

Wouter Maes, Toon Ghoos, Jurgen Kesters, Wouter Vanormelingen, Laurence Lutsen, Jean Manca, Dirk Vanderzande, Univ. Hasselt (Belgium)

In the field of polymer solar cells, improving photovoltaic performance has been the main driver over the past decade. To achieve high power conversion efficiencies, a plethora of new photoactive donor polymers and fullerene derivatives has been developed and blended together in bulk heterojunction photoactive layers. Simultaneously, further optimization of the device architecture and interlayer effects is also of crucial importance. In this respect, we report on the use of specific types of electron transport materials, imidazolium-substituted polythiophenes, to boost the inherent I-V properties of polymer solar cell devices, resulting in a considerable gain in overall photovoltaic output (20% increase in PCE up to an average value of 6.2% for PCDTBT:PC71BM). The beneficial effect is notably higher than for previously reported materials such as an analogous trimethylamine-functionalized ionic polythiophene or PFN. Best results were obtained for the highest molecular weight ETL material, pointing to an important influence of polymer chain length on ETL performance. Further progress in this direction by structural variation (counterion, monomer ratio, (block) copolymer configuration, extension to CPDT-based low bandgap polymers) is reported as well.

8830-46, Session 9

The effect of sterics and intermolecular interactions at the donor-acceptor interface on the performance of organic photovoltaics

Kenneth R. Graham, Stanford Univ. (United States) and King Abdullah Univ. of Science and Technology (Saudi Arabia); Clement Cabanetos, Abdulrahman El Labban, Guy Oliver Ngongang Ndjawa, Pierre M. Beaujuge, Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia); Michael D. McGehee, Stanford Univ. (United States)

Organic photovoltaics (OPVs) rely on the heterojunction between an electron donating material and electron accepting material to separate excitons into free electrons and holes. This interface is therefore critical to the performance of an OPV device, with the molecular conformation at this interface potentially playing a pivotal role in the charge separation and recombination dynamics. Although the molecular conformation at this interface is likely a determining factor in OPV performance, it remains relatively unexplored in most OPV systems. In this work we examine a series of benzodithiophene (BDT) and N-alkylthieno[3,4-c]pyrrole-4,6-dione (TPD) based copolymers, PBDTTPDs, with systematically varying sidechains. The variation of sidechains leads to significant differences in the morphology of bulk-heterojunction devices as probed through atomic force microscopy (AFM), transmission electron microscopy (TEM), and grazing incidence wide-angle X-ray scattering (GIWAXS). Although some variations in device performance may be ascribed to these nanomorphology differences, it appears that the sidechains also play a role in directing the molecular conformation between the polymer and fullerene. The effects of sidechains on the properties of the polymer-fullerene interface are explored through probing charge transfer state energies, with these results suggesting that the sidechains help to direct the molecular conformation at the polymer-fullerene interface. Furthermore, through making devices with low polymer concentrations in a fullerene matrix we are able to reduce the effects from nanoscale morphology variations, and these results further support a preferred molecular conformation that can be encouraged through appropriate sidechain substitutions.

8830-47, Session 9

Finely-tuning morphology of low band-gap polymer organic solar cells via mixed solvent

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Organic Photovoltaics have been gaining more and more importance in the energy field as a promising technology for low-cost, high-throughput, flexible energy generation process. In addition to materials novelty and device structure modification, morphology control of polymer: fullerene blend active layer is widely accepted as an efficient way for device performance improvement. Here, we report a new solvent mixture system for morphology tuning of diketopyrrolopyrrole (DPP)-based low bandgap polymer blended with PC71BM. Our study provides a new understanding of morphology control in organic bulk heterojunction.

Comparing to the widely used solvent system using 1, 8-diiodooctane (DIO) as additive, our solvent mixture system has significantly wider solvent composition window and higher degree of efficiency enhancement (25% in addition to efficiency acquired with DIO).We studied the conformational behaviors of DPP-based polymer and fullerene in the solution stage and during solid film formation stage in both solvent systems. Our results show that both solution state and film forming state morphology are important in determining the final bulk heterojunction morphology and they have distinct characteristics in both solvent systems. Thus the optimized performance is achieved via finely-tuning morphology through our solvent mixture system.

8831-101, Session 1

Industrial aspects of material development for organic field effect transistors *(Invited Paper)*

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It was in 1986, only a few years after the invention of an efficient synthesis of 3,6-diaryl-diketopyrrolopyrrole (DPP) that the term DPP (1) appeared in the pigment market. N,N-dialkyl-3,6-diheteroaryl-derivatives of DPP are suited as building blocks for conjugated polymers. This concept has been introduced for the first time in 2005. (2)

The presentation focuses on industrial aspects of the material development of DPP-Polymers for the application in solution processed field effect transistors. It will be shown that optimization of processing conditions can have a significant effect on transistor performance for a certain polymer. Although the solubility of DPP-Polymers is in general much higher than that of highly crystalline polymers like Poly-3-hexylthiophene (P3HT), transforming the polymer powder to a film is still challenging. Semiconductor film morphology and thus transistor performance strongly depends on it. Aspects of device integration, especially optimization of semiconductor interfaces to complementary materials, will also be discussed in this presentation.

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8831-102, Session 1

Isoindigo-based copolymers for field-effect transistors: the structure-property relationship *(Invited Paper)*

Jian Pei, Peking Univ. (China)

Organic field-effect transistors (OFETs) are advancing rapidly in terms of their applications in low-cost large-area thin film transistors. However, PFETs with high carrier mobility and long-time stability are usually achieved in low-humidity and inert atmosphere. Therefore, to design new polymers for high-mobility PFETs with ambient-stability is still of great challenge. On the other hand, the structure-property relationship is important for designing new organic materials for optoelectronics. Although several design strategies and even computational methods have been proposed for small molecular OFETs, rational design strategy for PFETs is seldom reported.

Herein, we develop isoindigo-based copolymers for PFETs to investigate their structure-property relationship. Owing to the donor-acceptor interaction and the spatial steric hindrance caused by the branched alkyl chains, we envision that the small units dock into the cavity formed by the isoindigo cores and branched alkyl chains. We systematically compare FET device performances, polymer packing and film morphologies of the polymers, and find that this strategy is efficient to obtain high-performance FETs. Polymers with C2h-symmetric donors exhibit systematically higher field-effect mobility than those with C2v-symmetric ones.

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8831-103, Session 1

V-shaped organic semiconductors having solution-processed high mobility and high thermal durability *(Invited Paper)*

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Printed electronics for the next-generation smart devices require development of solution-processable high-performance organic semiconductors. However, despite the enormous versatility in designing organic molecules, practical industrialization has not been achieved using existing compounds such as a variety of acenes and heteroacenes because of the significant difficulty in realizing the high mobility, solubility, thermal stability, and large-scale productivity at the same time. Therefore, an essentially new molecular design that satisfies all of the above requirements is required. Here, we have developed a conceptually new Bent-shaped π-conjugated systems containing a heterocycle ring at the center of the cores.

We first developed a facile and versatile synthetic methodology for a series of bent-shaped derivatives. Specifically, starting from 2-methoxynaphthalenes, the compound is simply synthesized in four steps containing three key reactions. Interestingly, DNT–V itself exhibits a solubility of 0.10 wt% in toluene even at room temperature. These alkyl-substituted DNT–V derivatives exhibited improved solubility in common organic solvents in the range of 0.12–1.73 wt%. C6– and C10–DNT–VW having two hexyl (C6) or two decyl (C10) chains at the 3 and 9 positions exhibited the obvious phase-transition temperatures of 197 and 150 °C, respectively, which is considerably higher than the values for other reported organic semiconductors. Their overall packing structures are typical herringbone-type forms, which resemble those of high-performance semiconductors such as pentacene and DNTT solids. Such conformation may be induced by two-dimensional intermolecular interactions. Solution-processed films based on such molecules have demonstrated high mobilities of up to near to 10 cm2 V–1 s–1. In addition, the design introduces a soluble high-mobility π-conjugated core, and we describe a large-scale applicable synthetic route and pronounced thermal stability inherent in the V-shaped cores.

8831-104, Session 1

New type of organic semiconductors for high performance organic field-effect transistors

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Great attentions have been paid to organic field-Effect transistors (OFETs) due to their potential applications in flexible displays, RFID, Smart cards, sensors, etc.[1] Organic semiconductors, as the key component of OFETs, are the base for high performance OFETs. Though great progress has been made, the lack of high performance organic semiconductors hinders the applications of OFETs.[2-3] Recently, we have developed series of high performance organic semiconductors.[4-9] We synthesized new type of thiophene based n-type organic semiconductors, the thin film transistors fabricated through solution technique exhibited high electron mobility (up to 0.9cm2/Vs) and high stability under ambient conditions. We also prepared a pentacene derivative which displayed high hole mobility, high current on/off ratio and low threshold voltage. In the presentation, these new results will be discussed.

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8831-105, Session 1

Liquid crystalline polymers based on pi-conjugated backbone for organic electronics

Fabrice Mathevet, Univ. Pierre et Marie Curie (France)

The self-organization of pi-conjugated organic materials forming highly ordered supramolecular architectures has been extensively investigated in the last two decades in view of optoelectronic applications. Indeed, the control of both the mesoscopic and nanoscale organization within thin semiconducting films is the key issue for the improvement of charge transport properties and achievement of high charge carrier mobilities. These well-ordered materials are currently either self-organized semiconducting polymers or liquid crystals.

In this context, we endeavored to investigate the self-organization of a side-chain liquid crystal (SCLC) semiconducting polymer where (i) the backbone is a pi-conjugated polymer and (ii) the side groups are pi-conjugated discotic mesogens.

Here we describe the design and synthesis of columnar side-chain liquid crystal homo and alternating (co)polymers with triphenylene mesogens as side groups, and well-defined regioregular polythiophene as backbone.

These different kinds of architectures prepared following the Grignard methathesis (GRIM), allow the control of the triphenylene side group ratio along of the polymer chains, and lead to tunable electronic properties and nanostructures.

In this work, we will give the details on the synthesis, structural characterization and morphology studied by Polarized-light Optical Microscopy (POM), Differential Scanning Calorimetry (DSC), Temperature-dependent small-angle X-ray diffraction and Atomic Force Microscopy (AFM). Moreover, their photophysical properties and the preliminary charge transport results will also be depicted in view of applications for organic optoelectronics.

8831-106, Session 1

Molecular tuning for organic transistors *(Invited Paper)*

John E. Anthony, Marcia Payne, Matthew Bruzek, Sean R. Parkin, Univ. of Kentucky (United States)

The critical relationships between intermolecular contacts and performance in thin-film transistors have been known for more than a decade. Several different approaches to controlling and tuning these solid-state relationships have been developed in the ensuing years, leading to high-performance semiconductors adopting both “herringbone” and “π-stacked” motifs in the solid state. We have previously shown how peri substitution of acenes induces pi-stacking and allows coarse control over crystal packing. In this talk, I will show how further substitution can be used to induce subtle tuning in the intermolecular contacts, and the impact of these changes on device performance. I will also describe our efforts to engineer the solid state orientation of dehydroannulenes, a class of materials heretofore unexplored for use in organic transistors.

8831-107, Session 2

Analysis of charge traps related to bias-stress stability of organic transistors *(Invited Paper)*

Kilwon Cho, Pohang Univ. of Science and Technology (Korea, Republic of)

We investigated the actual position and energy level of charge traps which decide bias-stress stability in organic transistors. It is firstly demonstrated that the polymer chain-ends of polymer gate-dielectrics(PGD) can trap charges. The drain current decay and the threshold voltage shift are found to increase as the molecular weight (MW) of PGD decreases. It is due to the variation in the density of polymer chain-ends in the PGDs with different MW; the free volumes at the polymer chain-ends allow the residence of water molecules, which significantly increases the density of charge-trap sites. Secondly, we present a novel strategy for analyzing bias-stress effects based on a four-parameter double stretched-exponential formula (DSE) and a photo-excited charge collection spectroscopy (PECCS). DSE yields two characteristic times and two stretched-exponential factors, thereby separating out the respective contributions from charge trapping events in semiconductors and gate-dielectrics. We found that the gate-dielectric layer, in general, plays a more critical role than the semiconductor layer in the bias-stress stability in early stage, possibly due to the wider distribution of the activation energy for charge trapping. Furthermore, using PECCS, one of the direct probing methods for deep trap, we successfully quantified the profile of the density-of-states of charge traps, separating out the energy levels of bias-stress-induced charge traps influenced by the interface and the organic semiconductor.

8831-108, Session 2

Device physics of advanced DPP polymer based transistors *(Invited Paper)*

Ananth Dodabalapur, Taejun Ha, The Univ. of Texas at Austin (United States); Prashant M. Sonar, A*STAR Institute of Materials Research and Engineering (Singapore); Seohee Kim, The Univ. of Texas at Austin (United States)

Co-polymers based on the diketopyrrolopyrrole (DPP) acceptor block are very promising for use in field-effect transistor applications. Such polymers have been shown to possess mobilities in the range 2-10 cm2/V-s by a few groups (albeit at high operating voltages and in long channel length devices). In this presentation we will describe results with new DPP-based polymers and specifically discuss the device physics of low voltage (< 10 V) and small channel length (< 5 microns) devices. We have been able to obtain mobility values of ~4 cm2/V-s in such devices at low operating voltages for channel lengths of 4 microns. These devices possess very high temperature field-induced conductivity of any polymer FET and which exceeds that of most organic single crystal FETs. This research was a result of understanding how to control the deleterious effects of Fröhlich polarons which tend to reduce mobility when high-k dielectrics are used with polymer semiconductors. Employing a thin interfacial low k dielectric, we are able to get record high mobilities. These devices also possess very low off-currents and a high on/off current ratio. Charge transport data and mechanisms will be discussed in detail including a new comprehensive theory of transport in polymer FETs that includes molecular polaron, dielectric polaron, and defect trapping effects.

8831-109, Session 2

Organic thin-film transistors for circuits in a foundry: process, charge transport phenomena and device library

Sebastian Pankalla, Simone Ganz, Edgar Dörsam, Manfred Glesner, Technische Univ. Darmstadt (Germany)

For the development of circuits consisting of organic thin film transistors (OTFT) with satisfying yield, a stable and reliable process is necessary. This can be achieved by eliminating failure mechanisms and understanding the charge transport phenomena in the individual device. At first, we present an analytical closed-form solution of the OTFT channel potential used for Monte-Carlo charge transport simulations and compute current-voltage characteristics out of it. Second, the layer deposition process influences the layer interface morphology. Therefore, velocity distribution measurements of the charge carriers lead to a simulation model with different disorder, depending on the layer surfaces and deposition techniques. The influence of the Schottky barrier height and contact morphology is simulated by finite-elements. It could be verified that the charge injection limiting contact resistance can be decreased by two orders of magnitude by reducing the thin oxide layer at the source and drain contacts and improving the semiconductor layer morphology at their vicinity. At last, leakage currents through the gate dielectric can be described by a poor conducting semiconductor model in the finite-elements framework. Leakage currents increase power consumption in circuits and, what is more critical, can lead to a total failure of the OTFT. However, they can be influenced by the number of deposited dielectric layers and charge injection supporting self-assembled monolayers at the source and drain contacts. These findings lead to circuit building blocks for an organic device library whereupon still existing performance fluctuations can be coped with Monte-Carlo circuit simulations.

8831-110, Session 2

Charge injection layers in organic light emitting transistors

Kristen Tandy, Mujeeb Ullah, Paul L. Burn, Paul Meredith, Ebinazar B. Namdas, The Univ. of Queensland (Australia)

Light-Emitting Field-Effect Transistors (LEFETs) are a class of next generation devices that combine the switching capability of a transistor with the emission properties of a light-emitting diode. Current LEFET performance is limited by inefficient charge injection and transport of electrons and holes from the requisite source and drain electrodes, leading to unbalanced charge transport and hence poor device performance. Here we report a simple method to reproducibly fabricate interdigitated source and drain electrodes of different workfunctions (one low and the other high) to tune charge injection and transport. Single and bilayer LEFET devices have been fabricated in the bottom gate configuration with top contact source and drain electrodes and the model emissive organic semiconductor Super Yellow as the active channel material. A custom made set of complimentary shadow masks were used in combination to alternatively evaporate the hole-injecting and electron-injecting contacts and form interdigitated finger structures. Sequential evaporations were performed using the two shadow masks exchanged between the deposition of the anode and cathode in each case. This allows nm thin electron and hole injection layers to be used with interdigitated contacts in the LEFET device architecture. The masks and holder deliver fixed alignment, with the same channel dimensions formed each time. The source and drain electrodes consisted of two layers - a metal top layer, with a further thin injection layer in direct contact with the Super Yellow. The injection layer was varied and included metals such as Ca, Ba and Sm, organic materials such as TPBI (1,3,5-tris(N-phenylbenzimidizol-2-yl)benzene), metal oxides (molybdenum oxide) or a salts such as Cs2CO3.

We show a high EQE of 1.2% with ON/OFF ratios of > 103 for single layer devices. For bilayer devices, we obtained a peak EQE of 0.05% and ON/OFF ratios of order 105 with a brightness of ~100 cd/m2. This is the highest optical light output with electrical switching performance obtained so far from single and bilayer LEFETs using a fluorescent material. In this presentation we will report the LEFET fabrication strategy, characterization of the devices, and in-depth analysis of the mechanism of operation.

8831-111, Session 2

Confocal photoluminescence microscopy for the study of exciton quenching in organic field-effect transistors

Stefano Toffanin, Wouter A. Koopman, Marco Natali, Stefano Troisi, Raffaella Capelli, Viviana Biondo, Andrea Stefani, Michele Muccini, Istituto per lo Studio dei Materiali Nanostrutturati (Italy)

Organic light-emitting transistor (OLET) is a novel multifunctional organic optoelectronic device which is gaining interest within the academic community as well as in industry. This unique device integrates the properties of a transistor with light generation. Even though recent breakthrough in OLET electroluminescence efficiency, little is known on how the device architecture influences the light formation processes. An increased internal efficiency compared to organic light-emitting diodes (OLED) is motivated by the shifting of the position of the charge emission zone faraway from the injecting contacts, thus avoiding exciton dissociation at the metal electrodes. Moreover, the high charge densities at the semiconductor-insulator interface potentially increase the obtainable exciton densities, which is a prerequisite for the realization of intense nanoscale light sources. On the other hand, high charge-densities also can result in enhanced exciton-quenching. For the further development of the OLET, it is of crucial importance to obtain information how the transistor architecture influences the light generation.

Here, we discuss an innovative and high-throughput experimental method for studying locale differences in exciton quenching within field-effect transistor active channel by implementing a confocal laser scanning fluorescence microscope upgraded for spatially localized lifetime measurements. Our results show that the quenching is dominated by polaron-exciton scattering, while electric-field mediated dissociation plays only a role at the proximity of electrodes. Indeed, photoluminescence quenching can be implemented in an active transistor for probing the induced charge distribution and estimate layer-thickness. In real ambipolar OLETs it is possible to correlate directly the recombination zone with the light-emission zone.

8831-112, Session 3

Exponential relation of PBTTT liquid crystalline correlation length with device performance *(Invited Paper)*

Harald W. Ade, North Carolina State Univ. (United States)

Bond anisotropy and orientation are critical parameters that strongly influence the electronic properties of many polymer-based devices, such as poly(2,5-Bis(3-alkylthiophen-2-yl)thieno[3,2-b]thiophene (PBTTT) thin film transistors. This is directly related to the high mobility along the one-dimensional back bone, some mobility along the pi-pi stacking direction, and very low mobility along the lamellar direction. To date, ordering in active layers of devices could only be characterized with X-ray or electron microscopy methods if the sample exhibited sufficient crystallinity. Here, we show that resonant scattering with polarized soft x-rays (P-SoXS) is not limited by the crystallinity in soft matter and can probe ordering of molecular orientation down to size scales below 10 nm [1]. We utilize its high sensitivity to probe the length scale of liquid crystalline ordering in PBTTT transistors. We find that charge mobility is exponentially dependent on the liquid crystalline correlation length. This correlation length relates more closely to device performance than other characteristics as probed by wide angle x-ray diffraction. We are in the

process of measuring the correlation length with P-SoXS for other high mobility materials and will present initial results. – We thank I. McCulloch and M. Heeney (Imperial College, UK) for providing the PBTTT.

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8831-113, Session 3

Solution coating aligned single-crystalline domains of strained organic semiconductor thin films *(Invited Paper)*

Ying Diao, Benjamin Tee, Stanford Univ. (United States); Stefan C. Mannsfeld, Stanford Synchrotron Radiation Lightsource (United States); Zhenan Bao, Stanford Univ. (United States)

Solution coating of organic semiconductors has a great potential for achieving low cost manufacturing of large area and flexible electronics. During the coating process, crystalline thin films of organic semiconductors are usually formed under kinetic conditions driven by the rapid solvent evaporation needed for high-throughput industrial-scale production. Yet, highly kinetic crystallization poses challenges to the control of thin film morphology. Two commonly encountered problems are mass-transport-limited crystal growth and uncontrolled nucleation. Both phenomena severely limit the electrical performance of organic semiconductors by introducing randomly distributed grain boundaries and structural defects. To address these challenges, we introduce a new approach for controlling morphology of solution printed thin films, wherein we design and engineer the fluid flow to enhance crystal growth and to control nucleus formation. We demonstrate for the first time a fast direct coating of patterned, millimeter-wide, centimeter-long, highly-aligned single-crystalline organic semiconductor thin films. Such a film morphology enabled an unprecedented average mobility of 8.1 ± 1.2 cm2 V-1 s-1 from lattice-strained single-crystalline domain thin films of 6,13-bis(triisopropylsilylethynyl) pentacene (TIPS-pentacene), with the maximum mobility reaching 11 cm2 V-1 s-1. This is also the first report of lattice-strained single-crystalline domain organic semiconductors achieved via solution processing.

8831-114, Session 3

Correlation between local morphology and electronic states in organic field-effect transistors investigated by charge modulation microscopy

Nicola Martino, Istituto Italiano di Tecnologia (Italy) and Politecnico di Milano (Italy); Calogero Sciascia, Alessandro Luzio, Istituto Italiano di Tecnologia (Italy); Valerio D'Innocenzo, Istituto Italiano di Tecnologia (Italy) and Politecnico di Milano (Italy); Maria Rosa Antognazza, Mario Caironi, Istituto Italiano di Tecnologia (Italy)

The morphology of the thin active layer is one of the main parameters that influence charge transport properties and thus the functioning of organic field-effect transistors (OFETs). To understand this relationship, it is desirable to have techniques able to locally probe the electronic properties along the channel of a working device. In this contribution we show that with Charge Modulation Microscopy (CMM)[1] it is possible to optically map the charge density in a high-mobility n-type OFET with a lateral resolution of about 500 nm; this is achieved by measuring the local polaronic absorption and bleaching features in a laser scanning confocal microscope. Interestingly, the signal is sensible only to the few-nanometers thick accumulation layer, allowing the investigation of the properties of the electronic states at the semiconductor-dielectric interface involved in charge transport processes. By using a polarized light probe, we highlight the presence of a micrometric texture in the map of the charge induced features, which can be related to regions of preferential alignment of the polymeric backbones. These regions of preferential alignment could play a crucial role in the transport properties of polymeric semiconductors, especially in novel n-type high-mobility materials in which the influence of morphology at different scales is currently highly debated.

8831-115, Session 3

Alkyl chain size and branching point influence over microstructure, morphology and charge transport in thieno[3,2-b]thiophene-diketopyrrolopyrole based polymers

Iain Meager, Imperial College London (United Kingdom)

Diketopyrrolopyrole (DPP) based polymers are well established as high performing materials in both solar cell devices and field effect transistors (FET). The electron deficient nature of the DPP core is desirable for donor-acceptor type polymers utilising molecular orbital hybridisation as a means to frontier orbital band gap reduction, with the planarity of the polymer backbone giving a good degree of pi-pi stacking.1 Solar cell devices fabricated from such materials have achieved efficiencies of >6%, whilst transistor mobilities routinely surpass 1cm2/Vs as demonstrated with the excellent results recorded in our group.2,3

Much effort has been dedicated to the fine-tuning of the electronic properties of such polymers yet the role of the solubilising alkyl chain is often overlooked. Herein is presented an extension of our group's work on thieno[3,2-b]thiophene-diketopyrrolopyrole (DPPTT-T) based polymers. By using larger chains and moving the branching position of the solubilising group on the DPP core higher molecular weight polymers are achieved and a larger range of comonomers can be accessed. Thus it is possible to selectively influence physical properties such as solubility and blend morphology whilst retaining the desirable energetic and optical characteristics previously achieved resulting in impressive and balanced transistor mobilities. The series of polymers are probed using state of the art diffraction, imaging and stability studies.

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8831-116, Session 3

Recrystallization kinetics in polythiophene thin films and implications for charge transport

Duc T. Duong, Stanford Univ. (United States); Victor Ho, Univ. of California, Berkeley (United States); Sonya Mollinger, Stanford Univ. (United States); Michael F. Toney, SLAC National Accelerator Lab. (United States); Rachel A. Segalman, Univ. of California, Berkeley (United States); Alberto Salleo, Stanford Univ. (United States)

Semiconducting polymers have been increasingly exploited for their potential in low-cost, solution processable electronic applications such as field-effect transistors (FETs) and light-emitting diodes (LEDs). In these devices the polymers are often casted from an organic solvent to form thin films on the orders of tens and hundreds of nanometers. However, a large number of deposition parameters can impact the final film morphology and the solvent-polymer interaction is extremely system-dependent. One method for circumventing this large parameter space is to melt and recrystallize the polymer film, which essentially removes all solvent history.

In this study we perform quantitative analyses of x-ray diffraction patterns and optical absorption spectra of poly(3-ethylhexylthiophene) (P3EHT) thin films. Here P3EHT is used for its slow crystallization kinetics, which is a rare property among semiconducting polymers. We are able to monitor the evolution of aggregates and crystallites as well as the recrystallization kinetics as a function of time. One of the unique aspects of semicrystalline, semiconducting polymer is that crystallites are highly anisotropic: the three directions of molecular order are (1) along the polymer backbone, (2) along the pi stacks and (3) along the alkyl stacking direction. As such we expect crystallite growth to also be anisotropic and this is indeed what we observe from our experimental results. Furthermore, we are able to comment on the mechanism with which the entire film recrystallizes and how film thickness and quenching temperature influence the crystallization kinetics and final film morphology. Finally the extracted structural properties are correlated to charge transport.

8831-117, Session 4

Ultra low-noise transport regime in organic molecular crystals *(Invited Paper)*

Vitaly Podzorov, Rutgers, The State Univ. of New Jersey (United States)

Small-molecule organic semiconductors form the basis for the emerging field of organic optoelectronics. In order to better understand the intrinsic photo-physical and transport phenomena in this important class of materials, it is necessary to study samples of very high structural order and chemical purity. Such materials exist in the form of molecular single crystals that can be used for fabrication of high-performance prototype devices, such as field-effect transistors, photo-conductors and photo-voltaic cells, in which intrinsic properties of organic semiconductors can be investigated without parasitic effects of disorder (see, e.g., [1,2,3]). This talk will present a novel method of surface functionalization that results in an extremely low-noise charge transport regime at the surface of molecular crystals, leading to an observation of unprecedentedly clean and quiet (low-noise) Hall effect.

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8831-118, Session 4

Transport in single crystal OFETs *(Invited Paper)*

C. Daniel Frisbie, Univ. of Minnesota (United States)

OFETs based on single crystals afford good opportunities to examine fundamental connections between charge mobility, molecular structure, and crystal packing. A particularly exciting recent development is the increase in the number of single crystal materials that exhibit OFET mobilities near 10 cm2/Vs, and also band-like behavior in that mobility increases as the device temperature decreases (up to a point). Observation of such large mobilities suggest that in these systems the intrinsic mobility is approached. In the first part of this talk will describe single crystal OFET measurements on a series of rubrene derivatives that have been designed so that the unit cell parameters are systematically tuned. The impact of the crystal structure on carrier mobility and the temperature dependence will be discussed. The second part of the talk will focus on transport in single crystal OFETs based on DNTT, a promising new organic semiconductor molecule that exhibits mobilities nearly as good as rubrene, the current benchmark material.

8831-119, Session 4

Light-emitting polymer/carbon nanotube hybrid transistors: below and above the percolation limit *(Invited Paper)*

Jana Zaumseil, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Hybrids of semiconducting polymers and single-walled carbon nanotubes (SWNT) are interesting for organic electronic devices such as solar cells, light-emitting diodes and field-effect transistors (FETs). They are easily produced by selective dispersion of SWNTs in polymer solutions by ultrasonication followed by centrifugation. We demonstrate that nanotubes at concentration levels well below the percolation limit significantly improve charge injection of both holes and electrons into semiconducting polymers in top-gate FETs. This leads to lower contact resistances and reduced threshold voltages, thus the maximum ambipolar currents and visible light emission due to electron-hole recombination are considerably enhanced. This effect can be maximized by patterning layers of pure carbon nanotubes onto the injecting electrodes before spincoating the pristine polymers leading to almost ohmic contacts for polymers, which usually exhibit highly Schottky barrier-limited injection. This improved injection of holes and electrons allows for a much wider range of accessible polymers for ambipolar and light-emitting transistors.

The same conjugated polymers can also be used to enrich specific semiconducting SWNT and to produce high-performance ambipolar nanotube network FETs. These show unusually efficient near-infrared emission. The obtained electroluminescence spectra show clear peaks depending on the enriched nanotube species but with a strong shift of intensity to SWNTs with longer emission wavelengths, i.e., larger diameters, compared to photoluminescence spectra of the same area. Mapping the emission from these networks during a gate voltage sweep allows us to visualize preferential current paths and investigate percolation models for purely semiconducting SWNT networks.

8831-120, Session 4

Nonvolatile transistor memory devices using high dielectric constant polyimides electrets

Ying-Hsuan Chou, Hung-Ju Yen, National Taiwan Univ. (Taiwan)

We report the nonvolatile memory characteristics of pentacene-based organic field-effect transistors (OFET) using high dielectric constant polyimide electrets, , PI(6FDA-TPA-CN), PI(DSDA-TPA-CN) and PI(BTDA-TPA-CN), consisted of electron-donating 4,4?-diamino-4?-cyanotriphenylamine (TPA-CN) and different electron-accepting dianhydrides. The dielectric constants of PI(BTDA-TPA-CN), PI(DSDA-TPA-CN), and PI(6FDA-TPA-CN) are 3.44, 3.52, and 3.70, respectively. Among the polymer electrets, the OFET memory device based on PI(6FDA-TPA-CN) exhibits the highest OFET mobility of 0.5 cm^2* V^-1* s^-1 due to the formation of the large grain size of the pentacene film by the hydrophobic surface. The OFET memory devices with the configuration of n+Si/SiO2/PI/Pentacene/Au show excellent nonvolatile behaviors for bistable switching. The stability for ON and OFF state can maintain 10^4 s with Ion/Ioff current ratios of 10^4 for PI(6FDA-TPA-CN). Moreover, the higher dipole moment and larger torsion angle result in the more stable charge transfer complex and accompany with the largest memory window of 84 V of the fabricated device. The write-read-erase-read (WRER) cycles can be operated over 100 cycles. The present study suggests that the high dielectric constant polyimide electrets with the enhanced capabilities for transferring and storing the charges have great potential applications for advanced OFET memory devices.

8831-121, Session 5

Synthesis and transport properties of new polymeric semiconductors *(Invited Paper)*

Antonio F. Facchetti, Polyera Corp. (United States)

Organic electronics is a new technology envisioning the fabrication of electronic devices using printing methodologies instead of conventional photolitography employed in the silicon industry. Since polymeric materials can be printed more efficiently than small molecules (they can be more easily formulated into inks with tuned viscosities) they will be the key enablers of this technology. In this presentation I will describe the design rationale, synthesis, characterization, and electrical properties of several new semiconducting polymers for printed thin-film transistors (TFTs). These polymers include new n-channel polymeric semiconductors containing dicarboximide functionalities, p-channel semiconductors based on new electron-neutral cores, and ambipolar polymers base on pi-extended monomers. This work demonstrates that printed TFTs are possible and exhibit promising charge carrier mobilities. Furthermore, printed, monolithically integrated all-polymeric CMOS circuits with good performance will be disclosed.

8831-122, Session 5

High performance field-effect transistors based on 2,6-diphenylanthracene (DPA) with thin film mobility up to 14 cm2V-1s-1 *(Invited Paper)*

Wenping Hu, Institute of Chemistry (China)

An anthracene derivative, 2,6-diphenyl anthracene (DPA), was successfully synthesized with three simple steps and high yield. The compound exhibited high thermal (up to 300 oC without decomposition) and environmental stability (HOMO = 5.6 eV). More attractively, field-effect transistors based on DPA films exhibited remarkable high performance, with mobility as high as 14.3 cm2V-1s-1, current on/off ratio >107 (up to 109) as well as long term stability. The high performance is assigned to the dense molecular packing of DPA and the high crystallinity of its films. The facile and high yield synthesis, high stability, and remarkable transistor performance in films, indicate the great potential of DPA for applications in organic electronics.

8831-123, Session 5

High performance liquid crystalline organic field effect transistor materials: How does the liquid crystallinity solve problems in conventional soluble OFET materials? *(Invited Paper)*

Hiroaki Iino, Takayuki Usui, Jun-ichi Hanna, Tokyo Institute of Technology (Japan)

No Abstract Available

8831-124, Session 5

Electronics by printing *(Invited Paper)*

Jie Zhang, A*STAR Institute of Materials Research and Engineering (Singapore)

It has been the mission for organic based functional materials development society that using low cost graphic arts printing technology to process functional devices for integrated circuits, solar cells, and light emitting devices. The reality is what device can be printed and how the printed devices performance. In this study, the team of scientists and engineers developed material systems, interface and process technologies that are able to print transistors, using graphic art printing technologies, with field mobility range from 0.8 to 2.4 cm2/V.s at the OFET channel length of 100 um. The subsequent logic and analog circuit are designed and fabricated based on the printed transistors. The circuit performances are evaluated. The design rule of the printed circuits, using graphic arts printing, is discussed.

8831-125, Session 5

Heteroannulenes: novel materials for organic field-effect transistors

Tarunpreet Singh Virk, Kamaljit Singh, Guru Nanak Dev Univ. (India)

In the course of development of cyclic conjugated chemical entities, structural variations of the fundamental tetrapyrrolic porphyrinoids by way of replacing pyrrole with other heterocyclic species and/or changing the topology of the macrocyclic framework in a manner that p-electron conjugation pathway is maintained, has led to the synthesis of potentially rich families of neutral as well as charged heteroannulenes. We have disclosed the electronic structure and demonstrated the use of meso-aryl tetraoxa[22]annulene[2,1,2,1] (1) and tetrathia[22]annulene[2,1,2,1] (2) as thin film organic field-effect transistors (OFETs). These molecules showed moderate to high on/off ratio along with a high reproducible bulk-like carrier hole mobility. The tetrathia annulenes also showed weak interaction with the electron accepting TCNQ as shown by X-ray crystal structure. Such a molecular level hetrojunction (3), showed air stable ambipolar charge transport behaviour. Further the tailoring of the tetrathia annulenes has been done by appending the electron withdrawing substituents to them which led to improvement of their on/off ratios along with good to high hole mobility, a characteristic required for application in switching (2). The details of designs of macrocyclic entities, structure, physical properties, charge mobility characteristics as well as chemosensing behavior shall be presented.

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8831-126, Session 6

Exploration of new building units for high-performance semiconducting polymers *(Invited Paper)*

Itaru Osaka, RIKEN (Japan)

Exploration of new building units is crucial for the development of high-performance semiconducting polymers. Since semiconducting polymers for p-channel transistors are required to have deep HOMO level as well as high crystalline structures, key building units are relatively “weak” donor (electron-rich) and relatively “strong” acceptor (electron-poor) units that ensure strong intermolecular interactions. In this presentation, we show the synthesis, characterization, properties, thin film structures, and transistor performances of semiconducting polymers based on several new building units, namely, napthodithiophene (NDT) as the donor, and naphthobisthiadiazole (NTz) and thienothiophenedione (TTD) as the acceptor. The polymers exhibited quite high charge carrier mobilites of 0.5–1.4 cm2/Vs. The correlations between the polymer structure, electronic structure, crystallinity, and charge transport properties will be discussed.

8831-127, Session 6

Development of a new polymeric semiconductor material: characterization, performance, and application *(Invited Paper)*

Mingqian He, James R. Matthews, Robert A. Bellman, Kristi L. Simonton, Weijun Niu, Arthur L. Wallace, Jieyu Hu, David N. Schissel, Michael J. Winningham, John C. Mauro, Corning Incorporated (United States); Hon Hang Fong, Shanghai Jiao Tong Univ. (China); Wen-ya Lee, Zhenan Bao, Stanford Univ. (United States)

A new fused-thiophene diketopyrrolopyrrole based semi-conducting polymer has been designed and synthesized. Many synthetic challenges were overcome in the development of a practical scalable synthesis of this new material. Characterization by GPC over a range of temperatures has revealed the tendency of this polymer to aggregate even at elevated temperatures and confirmed that the final values obtained for molecular weight are for non-aggregated material. The ability to obtain accurate molecular weight information makes it possible to study the relationship between mobility and molecular weight. This polymer shows great solubility in many different hydrocarbon solvents, while also giving excellent device performance with very high mobilities when deposited from those solvents. The polymer has also been studied on different substrate materials, including those not amenable to traditional electronics, to explore potential new applications.

8831-128, Session 6

Engineering charge transport in organic and nanocrystal semiconductor thin films for flexible electronics *(Invited Paper)*

Cherie Kagan, Univ. of Pennsylvania (United States)

Organic and inorganic nanocrystals are being aggressively pursued as semiconducting materials in low-cost, large-area, flexible electronics. These materials classes are solution-processable enabling their deposition by coating, printing and assembly methods that facilitate their integration in devices and on large-area, flexible plastics. We report chemical routes to engineer materials and device interfaces to manipulate carrier type and mobility to realize high-performance, unipolar p-type and n-type and ambipolar behavior in organic semiconductors and semiconducting nanocrystals for field-effect transistors (FETs). We have integrated FETs as building blocks to realize high gain single organic semiconductor circuits and demonstrated the first nanocrystal integrated circuits.

8831-129, Session 6

New thiophene-diketopyrrolopyrrole based acceptor-donor-acceptor conjugated materials for high performance field effect transistors

Chien Lu, National Taiwan Univ. (Taiwan)

We report the synthesis, morphology, and field effect transistor (FET) characteristics of new acceptor-donor-acceptor conjugated materials, consisted of diketopyrrolopyrrole (DPP) acceptor and four different donors , dithiophene (2T), thieno[3,2-b]-thiophene (TT), dithieno[3,2-b:2',3'-d]-thiophene (DTT), and 5,5'''-di-(2-ethylhexyl)[2,3';5',2'';4'',2''']quaterthiophene (4T). The optical band gaps (eV) of the prepared materials are lower than 1.7 eV, attributed by strong donor/acceptor intramolecular charge transfer and the backbone coplanarity of the thiophene moieties. The order of the crystallinity is TT2DPP > 4T2DPP?2T2DPP > DTT2DPP, resulted from the cis/trans-stereo-structure. TT2DPP and 2T2DPP belong to the trans-stereo structure but DTT2DPP with the cis-stereo structure, which probably leads to different crystallinity. On the other hand, 4T2DPP with the biaxial structure exhibits different lamellar diffractions compared to 2T2DPP. The conjugated materials show well-interconnected small nanorods. The FET devices after thermal annealing exhibit the hole mobility of 3.73?10-2 , 8.38?10-2, 1.62?10-2, and 6.02?10-2 cm2V-1s-1 for 2T2DPP, TT2DPP, DTT2DPP, and 4T2DPP, respectively, which is consistent with the order of the crystallinity. In addition, the FET?hole mobility of TT2DPP is improved to 0.1 cm2V-1 s-1?through solution-shearing. The experimental results suggest the potentials applications of the new DPP-thiophene-DPP conjugated materials for organic electronic devices.?

8831-130, Session 6

Tuning rubrene crystal structures via polymer binders and its applications in organic field effect transistors

Pil Sung Jo, Duc T. Duong, Joonsuk Park, Robert Sinclair, Alberto Salleo, Stanford Univ. (United States)

Solution processable organic semiconductors are very promising materials because of their potential applications such as RFID tags and electronic paper. Among organic semiconductors, 5,6,11,12-tetraphenylnaphthacene (rubrene) has very high field effect mobilities (~20 cm2 V-1 s-1) in the form of single crystal fabricated by vacuum methods. However, only a few solution methods for fabricating rubrene devices have been reported. Among the reports, devices based on a blend of rubrene with polystyrene polymer and glass forming diluents exhibit moderate mobilities (>0.1 cm2 V-1 s-1) considering that the devices are thin films. To my knowledge, however, there have been no attempt to understand the effects of the type of the polymer on rubrene crystallization and the resulting device performance.

Here, we investigate polymer binder effects on phase separation, crystallization, and resulting electrical properties of rubrene in organic field effect transistors. Rubrene was blended with three different amorphous polymers: polystyrene (PS), poly(methyl methacrylate) (PMMA), and poly(4-vinylpyridine) (P4VP). The blends were spin-cast and then thermal annealed to induce crystallization. Depending on the polymer binder, different crystal structures of rubrene were observed with X-ray and electron diffraction techniques. To measure the electrical properties of the rubrene / polymer, bottom-gate and top-contact field-effect transistors were fabricated. Among the three blends, devices based on rubrene / PS have the highest mobilities (?ave = 0.5 cm2 V-1 s-1) while those based on rubrene / PMMA did not result in any working devices. For industrial applications, patterning of rubrene / PS was also demonstrated by spin-coating on chemically patterned substrates.

8831-131, Session 7

Chain conformations dictate multiscale charge transport phenomena in disordered semiconducting polymers *(Invited Paper)*

Andrew J. Spakowitz, Stanford Univ. (United States)

Semiconducting polymers play an important role in a wide range of optical and electronic material applications. It is widely accepted that the polymer ordering impacts charge transport in such devices. However, the connection between molecular ordering and device performance is difficult to predict due to the current need for a mathematical theory of the physics that dictates charge transport in semiconducting polymers. Here, we present a new analytical and computational description in which the morphology of individual polymer chains is dictated by well-known statistical models and the electronic coupling between units is determined using Marcus theory. This effort combines our research group's modeling efforts in polymer conformational properties and reaction-diffusion phenomena to address the multiscale dynamics of charge transport in a heterogeneous material. The resulting model is capable of bridging molecular-level charge transport mechanisms to large scale transport behavior, thus facilitating direct comparison with experiments. The multiscale transport of charges in these materials (high mobility at short length scales, low mobility at long length scales) is naturally described with our framework. Additionally, the dependence of mobility with electric field and temperature is explained in terms of conformational variability and spatial correlation. Our model offers a predictive approach to connecting processing conditions with transport behavior.

8831-132, Session 7

Using synchrotron x-ray scattering to discover the molecular packing in high performance organic semiconductor thin films *(Invited Paper)*

Stefan C. Mannsfeld, SLAC National Accelerator Lab. (United States)

In polycrystalline thin films of small organic semiconductor molecules, the precise molecular packing determines the film's intrinsic charge transport properties and consequently the electrical performance in thin-film devices such as organic thin film transistors (OTFTs). Synchrotron X-ray scattering is a powerful method to extract molecular packing details in such films that cannot currently be obtained by any other available technique. It can, in fact, be used to analyze films as thin as a fraction of a single monolayer. We employ a combination of Grazing Incidence X-ray Scattering (GIXS) and advanced crystallographic refinement calculations to obtain a detailed picture of the molecular packing at the emiconductor/dielectric interface in OTFT thin films.

The capability to obtain the detailed molecular packing with this approach is highlighted at the example of several organic semiconductor thin film systems, including high performance solution-deposited materials, both n-type and p-type, that exhibit field effect mobilities > 3 cm^2/Vs in the respective OTFT devices. In vacuum-deposited monolayer films of alkylated short oligoacenes on silanized SiO2 surfaces, our approach reveals a marked odd-even effect in the molecular packing. Finally, we discuss the implementation of in-situ printing of OTFT thin films directly at the beam line as a tool that allows us to study the crystallization kinetics and morphology formation during the drying of the ink.

8831-133, Session 7

On the phase behaviour of organic semiconductors and its influence on organic transistor performance *(Invited Paper)*

Natalie Stingelin-Stutzmann, Imperial College London (United Kingdom)

The physical organisation, from the molecular to the macro-scale, of functional organic matter such as polymer semiconductors can profoundly affect the properties and features of the resulting architectures and their consequent performance when used as active layers in organic optoelectronic devices, including organic thin-film field-effect transistors, organic light-emitting diodes or organic photovoltaic cells. Here, we present a survey on the principles of structure development from the liquid phase of this interesting and broad class of materials with focus on how to manipulate their phase transformations and solid-state order to tailor and manipulate the final 'morphology' towards technological and practical applications. We will discuss blending, nucleation and use of processing aids to control the microstructure targeted for field-effect transistor applications.

8831-134, Session 7

New insights into solution processing of organic semiconductors *(Invited Paper)*

Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia)

As solution processing of high performance organic thin film transistors (OTFTs) emerges as a viable alternative to vacuum deposition, there is increasing urgency to develop robust and reproducible manufacturing processes compatible with large area substrates. This requires a fundamental understanding of the underlying mechanisms of solution processes including solution-to-solid phase transformation as the solution dries. This talk will present our latest investigation of OTFTs based on small molecules and blends (small-molecule & polymer) prepared using commonly-used lab-based solution processing methods, namely drop-casting, spin-coating and blade-coating. We will explore commonalities and describe key differences in the initiation and mechanisms of thin film formation, leading to significant differences in microstructure and phase separation, as well as dramatic implications on carrier transport in both top- and bottom-contact device scenarios.

8831-135, Session 8

High performance organic electrochemical transistors *(Invited Paper)*

Jonathan Rivnay, George G. Malliaras, Ecole Nationale Supérieure des Mines de Saint-Étienne (France)

Large amplification and fast response are essential for transistors in applications ranging from switching elements to measurement of fast biological events such as neuronal action potentials. To this end, organic electrochemical transistors (OECTs) based on conducting polymers such as PEDOT:PSS {poly(3,4-ethylenedioxythiophene) doped with poly(styrenesulfonate)} have been recently targeted for applications in environmental and biological sensing due to their efficient ionic to electronic signal transduction in aqueous. OECT operation relies on the modulation of drain current by the de-doping of PEDOT upon application of a gate bias (which causes a drift of cations into the bulk of the channel). Such operation is notably different other electrolyte-gated TFTs which largely rely on interfacial ion accumulation to enhance the field effect. Efficient OECT operation requires fast electronic pathways for holes, and hydrated phases for mobile ion drift. However, relatively little is known of the solid state and hydrated structure of PEDOT:PSS relevant for electronic and ionic transport. Through active material structure-property investigations as well as micron-scale fabrication and optimization we present a solution processed organic electrochemical transistor with a transconductance approaching 4 mS, and a broad/invariant frequency response from steady state to 5-10 kHz. With proper device design, PEDOT-based OECTs can be made to completely shut off: exhibiting 10mV/decade sub-threshold slopes and on:off current ratios exceeding 10^4. The relative ease of fabrication and ability to embed active devices in thin polymeric substrates allows for extreme flexibility, maintaining high performance after aggressive crumpling. Along with stable operation in vivo and in cell culture, such characteristics make OECTs ideal candidates for low signal, transient biological recordings.

8831-136, Session 8

Tuning polarity and improving charge transport in organic semiconductors *(Invited Paper)*

Joon Hak Oh, A-Reum Han, Hojeong Yu, Eun Kwang Lee, Moon Jeong Jang, Ulsan National Institute of Science and Technology (Korea, Republic of)

Tuning dominant polarity of charge carriers and improving their mobilities are of great importance for realizing on-demand, target-specific, high-performance organic circuitry. The ability to selectively tune the dominant polarity of organic semiconductors enables a range of practical applications such as tailor-made p-n junctions and complementary metal oxide semiconductor (CMOS)-type organic logic circuits which offer various advantages including sophisticated control of current-voltage characteristics, lower power dissipation, greater operation speed, and higher stability. In addition, chemical or biological sensors based on polarity-tunable organic semiconductors can obtain the benefit from the selective manipulation of the electrical signals transduced by the analyte binding events. In particular, ambipolar polymer semiconductors provide a number of advantages for the cost-effective production of CMOS-type circuits as they can be deposited in the simplest single processing step, while maintaining the attractiveness of easy solution processing. Herein we report viable approaches to selectively tune the dominant polarity of charge carriers in solution-processed ambipolar organic field-effect transistors (OFETs). In addition, we introduce our molecular design strategies for achieving efficient charge transport in organic semiconductors, which embraces the rational design of conjugated backbones, the side-chain dynamics, and the crystallinity control of the active layer.

8831-137, Session 8

Printed electronics devices and their manufacturing *(Invited Paper)*

Janos Veres, Palo Alto Research Center, Inc. (United States)

No Abstract Available

8831-138, Session 8

Printing technique dependent charge carrier velocity distribution in organic thin film transistors

Simone Ganz, Sebastian Pankalla, Manfred Glesner, Edgar Dörsam, Technische Univ. Darmstadt (Germany)

Charge carrier velocity distribution was investigated in printed organic thin film transistors. We found a direct dependency of the velocity distribution on the surface morphology of the semiconductor, which reflects the interface between the semiconductor and the dielectric and thus the actual transistor accumulation channel. The effects of flexographic and gravure printing compared to spin coating have been investigated. The surface morphologies differ in waviness and surface roughness due to the respectively used deposition process. The surface was not only varied in the deposition technique itself, but also by changing of cell volume, solid content of the semiconductor formulation and number of printed dielectric layers. The investigated transistors were built in top gate bottom contact architecture. Therefore we replaced the spin coating processes for the organic semiconductor and the dielectric step by step by printing processes to cross-match the investigated layers. Several identical transistors of each kind of process combination were investigated and a compared. The velocity distribution broadens towards slower charges for printed semiconductor layers. Compared to the spin coated ones, printed semiconductor layers show an increased waviness of the surface resulting in an increased interface between the semiconductor and the dielectric on the one hand, and an increased disorder of the semiconductor on the other. In contrast to that we found out that the deposition technique of the dielectric does not seem to influence the charge carrier velocities in the same way.

8831-139, Session PWed

Lateral solidification of a liquid crystalline semiconductor film induced by temperature gradient

Tomoya Hoshino, Hayato Ito, Ichiro Fujieda, Tomonori Hanasaki, Ritsumeikan Univ. (Japan)

Derivatives of [1]benzothieno[3,2-b]benzothiophene (BTBT) are attracting much attention as a highly soluble, high-mobility semiconductor material for thin-film transistor applications. These small molecules are known to organize themselves into a single crystalline structure after spin coating or drop casting. Charge transport in a single crystal material is anisotropic in nature. Hence, it is desired to control its orientation during growth or recrystallization so that the source and drain electrodes of a transistor are to be placed along a faster transport direction. We propose to generate temperature gradient in a heated liquid crystalline thin film to induce lateral recrystallization. In experiment, we tried two methods. First, an aluminum plate with two narrow ridges was inserted between a temperature-controlled stage and a square silicon substrate with a 200nm-thick SiO2 and a spin-coated C8-BTBT film. We raised the temperature of the stage to 120 C and let it cool gradually. During cooling at around 105 C, the color of the sample started to change, indicating a phase change. This change proceeded from the four corners of the film and in about 30 seconds, the darker regions merged at the center of the substrate. Second, the same sample was placed at the edge of the stage. In this case, the color change started from the protruding corner of the sample and proceeded toward the other end. Micrograph observation revealed that cracks were formed in these films and they were perpendicular to the direction of the phase change.

8831-140, Session PWed

Screen printing and mechanical polishing of silver contacts for the organic transistor array

Boyu Peng, Jiawei Lin, Paddy K. L. Chan, The Univ. of Hong Kong (Hong Kong, China)

Organic transistor device is a high potential candidate for information storage and sensing applications. Low fabrication cost makes it possible for large area and mass production. Due to the requirement of vacuum deposition or intrinsic limitation of materials, it is difficult to use methods like thermal evaporation or sputtering to achieve large area production in short period of time. In this work, we fabricated large area transistor array based on screen printing and other solution processing methods. With the high resolution printing mesh, we are able to form a 50 ?m transistor channel. Without thermal annealing, the printed silver contacts show resistivity below 10E-4 ?•cm. We also further investigated the reduction of the printed silver thickness and surface roughness by applying mechanical polishing to screen printed Ag gate electrode. We can significantly reduce the surface roughness (rms) from ~150nm to ~10nm. As the solvent content in the Ag paste is less than 10%, instead of using bottom source drain contact, we can screen print the top contact source and drain electrodes onto the organic semiconductors directly without sacrificing the contact resistance. The screen printing parameters, detailed device structures and the connection of the devices will also be discussed.

8831-141, Session PWed

Thin film transistors based on self-assembled monolayer modified organic and oxide semiconductor structures fabricated by an inkjet printing method

Yong Suk Yang, In-Kyu You, Hye-Min Kim, Seung Young Oh, Hee Yeon Noh, Electronics and Telecommunications Research

Institute (Korea, Republic of)

- Developement of interface between Ag source-drain metal and semiconductor.
- Ink-jet printing conditions carefully controlled to maximize device performance.
- Study of the interface topologies for the so formed TFTs

8831-142, Session PWed

Two-dimensional analytical modeling of non-linear charge injection in bottom-contact organic field-effect transistors

Franziska Hain, Technische Hochschule Mittelhessen (Germany)

The interest in organic field-effect transistors has grown enormously during the last years. However, analytical compact models of organic transistors suitable for circuit design tools are rarely to find and mostly not able to describe the impact of physical/chemical effects on the electrical device performance sufficiently.

In dependence of different source and drain materials, varying workfunctions, HOMO, LUMO and trap levels the parasitic contact resistance effects became a major problem in organic transistors. So the source semiconductor junction was considered to be the limiting factor for the current flow.

Instead of simply applying well-known compact models of silicon MOSFETs, in our modeling work we followed a fundamental physics-based approach, taking into account the special mechanisms of current transport in organic transistors.

We assumed metallic source and drain electrodes and a random hopping system with localized states e.g. a conjugated polymer as semiconductor.

As the main charge transport mechanisms at the source semiconductor contact we assumed tunneling and drift diffusion processes. The two-dimensional shape of the barrier has been analytically calculated by solving the Poisson equation via the conformal mapping technique.

Following the multiple trapping and release model we assumed that in the channel area the charge transport is only limited by grain boundaries and traps located close to them. In our model we consider these traps with discrete levels at the grain boundaries.

The model results are in good agreement with measurement results published by third parties.

First test structures were printed and are yet to be multiplied.

8831-143, Session PWed

Aging effects on an organic fully printed complementary voltage controlled oscillator

Mathieu Guerin, Emmanuel Bergeret, Evangeline Bènevent, Philippe Pannier, Institut Materiaux Nanoelectronique de Provence (France); Anis Daami, Romain Coppard, Commissariat à l'Énergie Atomique (France)

We present in this abstract an organic fully printed complementary voltage controlled oscillator (VCO). This VCO is completely manufactured by means of mass printing techniques on flexible substrates and consists of a chain of seven looped CMOS inverters. The VCO oscillates at a frequency of 203 Hz with a voltage supply value of +/-20V.

The modelling of devices composing the circuit was made using a-Si TFT model model, then simulations and layout of the circuit were carried out with the Cadence virtuoso suite.

The fabrication process used screen-printing operations for depositing the organic semi-conductor and dielectric materials on a PEN sheet. The whole manufacturing process is made in ambient air.

Since circuits lifetime is one of the most important issues in organic electronics, a study has been performed during one year in order to follow the effects of aging on the circuit performances. The VCO's oscillations were measured right after manufacturing and one year after. The oscillations showed an increase in frequency from 203 Hz to 250 Hz in one year.

In order to explain this behaviour, DC measurements were performed on single transistors made on the same plastic sheet. The measurements made on these one-year-aged transistors showed a decrease of the voltage threshold (Vt) value. This Vt shift explains the frequency change according to the VCO's frequency equation.

The robustness of the presented voltage controlled oscillator is demonstrated since the circuit still oscillates one year after fabrication. The frequency increase is easily explained by the transistors threshold voltage decrease.

8831-144, Session PWed

Coplanar-gate transparent graphene transistors and inverters on plastic

Beom Joon Kim, Seoung-Ki Lee, Sukjae Jang, Sungkyunkwan Univ. (Korea, Republic of); Moon Sung Kang, Soongsil Univ. (Korea, Republic of); Jong-Hyun Ahn, Jeong Ho Cho, Sungkyunkwan Univ. (Korea, Republic of)

Transparent flexible graphene transistors and inverters in a coplanar-gate configuration were presented for the first time using only two materials: graphene and an ion gel gate dielectric.

The novel device configuration simplifies device fabrication such that only two printing steps were required to fabricate transistors and inverters. The devices exhibited excellent device performances including low-voltage operation with a high transistor-on current and mobility, excellent mechanical flexibility, environmental stability, and a reasonable inverting behavior upon connecting the two transistors.

8831-145, Session PWed

Stretchable organic thin-film transistors using inkjet printing method

Soon-Won Jung, Bock Soon Na, Chan Woo Park, Sang Chul Lim, Ji-Young Oh, Jae Bon Koo, Electronics and Telecommunications Research Institute (Korea, Republic of)

Stretchable electronic devices are advanced electronic devices which may maintain electrical functions, even in the case that substrates are expanded or contracted when external stress is applied thereto. A technique for stretchable electronic circuits, differing from typical flexible devices only having a bendable function, has applicability in various fields, such as sensor skin for robots, wearable communication devices, implantable or wearable bio-devices, or advanced displays. A technique of securing stretchability of a device by forming wrinkles on a substrate having circuits formed thereon, a technique of using a stretchable conductive organic material having conductivity instead of metal interconnections, or a technique of patterning metal interconnections in the form of stretchable two-dimensional planar spring may be required in order to realize stretchable electronic devices. In this study, we have demonstrated that top-gated stretchable thin film transistors can be fabricated onto polydimethylsiloxane (PDMS) substrates. Source and drain electrodes were embedded in an elastomer substrates.

8831-146, Session PWed

Effect of dielectric/organic interface properties on charge transport in organic thin film transistors

Ronak Rahimi, Dimitris Korakakis, S. Kuchibhatla, West Virginia Univ. (United States)

Charge carrier transport within the organic thin films as well as charge carrier injection between organic layers and organic/inorganic materials such as metal or dielectric layers are crucial factors in determining the efficiency of organic electronic devices. These parameters rely largely on the molecular structure, morphology and ordering of the organic thin films. Therefore, a profound understanding of the structure of organic materials as well as the properties of the interfacial layers is crucial to enhance the performance of the device. To achieve this feat, structure and morphology of PTCDI-C8 and pentacene thin films on Lithium Fluoride (LiF) have been studied using X-ray reflectivity (XRR) and Raman spectroscopy techniques. These films have been integrated into organic thin film transistors (OTFTs) to investigate their transport properties. The structural characterization revealed that the PTCDI-C8 films form an ordered structure on the LiF dielectric layer. Devices with LiF/PTCDI-C8 bilayer exhibit about one order of magnitude higher output current (Ids) at a constant drain-source voltage (Vds) compared to the devices with LiF/pentacene bilayer. The observed differences in the electrical characteristics of these devices can be attributed to the effects of the dielectric/organic interface and the molecular structure of the organic layers. The results of this study present the importance of the dielectric/organic interfaces in the performance of OTFTs.

8831-147, Session PWed

Optimization of aerosol jet printing for high resolution, high aspect ratio silver lines

Ankit Mahajan, C. Daniel Frisbie, Lorraine Francis, Univ. of Minnesota, Twin Cities (United States)

Aerosol Jet Printing is a recent direct write method that produces feature sizes smaller than the traditional inkjet and screen printing processes. In this technique, the ink is converted to a fine aerosol, and this aerosol mist is directed to a deposition head in a flowing carrier gas. Inside the deposition head, an annular sheath gas focuses the mist to produce a high density deposit with feature size only a fraction of the nozzle. In this paper, the influence of the process parameters on the geometry of aerosol-jet printed silver lines is explored. We demonstrate that the concept of focusing ratio, the ratio of the sheath gas flow rate to the carrier gas flow rate, is central to controlling line features and resistances. Line width decreases upon increasing the focusing ratio; but the thickness increases simultaneously. Both line width and thickness decrease with increasing stage speed. Geometry control also controls the resistance per unit length of the printed lines. The results are condensed into an operability window and region for printing tall and narrow lines in a single pass is identified. Lines as narrow as 20 µm and aspect ratio (thickness/ width) greater than 0.1 are obtained under optimized conditions.

8831-148, Session PWed

Organic memory transistor based on hybrid dielectric

Xiaochen Ren, The Univ. of Hong Kong (Hong Kong, China)

Organic memory devices are known as promising devices for next generation date storage applications due to their flexibility and low fabrication cost. For the transistor based memory devices, by using the hybrid dielectric containing polymer electrets layer, the threshold voltage of memory transistor can be well controlled at the same time having good data retention property and short programming time. However, the physics of traps state in polymer electrets are not well understood and the relative large programming voltage of polymer electrets limits the application of this type of memory devices. We have fabricated the hybrid transistor memory device based on SiO_2 and polystyrene (PS) hybrid dielectric. The trap states density as a function of polymer thickness and molecular weight of PS has been investigated and a maximum 100V memory window between programming and erasing is realized. Furthermore, in order to meet the requirement of portable electronic devices, the capacitance of dielectric material for memory transistor must be higher to reduce the operating voltage. Owing to the high permittivity of Al_2O_3, we fabricated the organic memory transistor based on anodized Al_2O_3/self-assembly monolayer (SAM)/PS hybrid dielectric, the effective capacitance of hybrid dielectric is 210 nF/cm2 and the transistor can reach saturation state at negative 4V gate bias. Spun coated PS on SAM treated surface can form thinner layer compared to the one on untreated Al_2O_3 surface therefore the hybrid dielectric can maintain high capacitance. The memory window in transfer curve is around 1V under +/-5V programming and erasing bias. We will also discuss the potentially applications in large area electrical skin.

Conference 8831B: Organic Semiconductors in Sensors and Bioelectronics VI

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8831-201, Session 1

Probing the absorption and release of nitroaromatic vapours from carbazole-based fluorescent dendrimer films *(Invited Paper)*

Paul L. Burn, Paul Shaw, Paul Meredith, The Univ. of Queensland (Australia); Michael James, Australian Synchrotron (Australia); Ian R. Gentle, The Univ. of Queensland (Australia)

We present a study into three generations of fluorescent carbazole-based dendrimers that exhibit strong binding with nitroaromatic compounds accompanied by photoluminescence (PL) quenching, making them attractive sensing materials for the detection of explosives such as 2,4,6-trinitrotoluene (TNT). The absorption and release of the (deuterated) TNT analogue, 4-nitrotoluene (pNT), from thin films of the dendrimers were studied with a combination of time-correlated neutron reflectometry and PL spectroscopy. When saturated with pNT the PL of the films was quenched and could only be recovered with a nitrogen gas flow upon heating to 40-80° C. Although the majority of the absorbed pNT was removed by this method the neutron reflectometry showed that the recovered films still contained residual quantities of pNT. However, the proportion of the PL recovered increased strongly with generation with the third generation dendrimer exhibiting full recovery. This result is attributed to a combination of two effects. Firstly, the dendrimer films present a range of binding sites for nitroaromatic molecules, with molecules bound to the higher energy sites remaining after the thermal recovery. Secondly, the exciton diffusion coefficient decreases with dendrimer generation, inhibiting the PL quenching by the bound pNT.

8831-202, Session 1

Design, synthesis, and static charge tuning of organic semiconductors for sensing applications *(Invited Paper)*

Howard E. Katz, Weiguo Huang, Kalpana Besar, Thomas Dawidczyk, Johns Hopkins Univ. (United States)

Organic and polymeric semiconductors are among the alternatives to silicon being considered for sensing devices and circuitry. Their synthesis is now well established, and some performance metrics such as charge carrier mobility and optoelectronic quantum yield exceed those of inorganic counterparts such as amorphous silicon. The best fit for organic semiconductors is in applications where inherent capabilities such as rational modification of carrier energy levels and covalent connection between charge channels and surface receptors are leveraged.
This presentation will describe newly synthesized organic molecular solids and polymer films where these attributes are emphasized. For example, introduction of highly electron donating tetrathiafulvalenes into moderately electron-rich polymers enhances response to electron-poor analytes, and addition of a borane to a semiconductor enhances response to ammonia, for the development of chemical sensors. Carrier energy levels are markedly and predictably altered by static charge embedded in polystyrene films adjacent to organic semiconductors, multiple device activities to be obtained from a single device layout using one semiconductor, and also the avoidance of powering gate electrodes to set the optimal sensitivities during operation. Finally, approaches to optimizing water stability and aqueous-media responses will be discussed.

8831-203, Session 1

Photostable organic fluorescent dots with aggregation-induced emission characteristics for non-invasive long-term cell imaging *(Invited Paper)*

Ben Zhong Tang, Hong Kong Univ. of Science and Technology (China)

Long-term non-invasive cell tracing by fluorescent probes is of great importance to understand genesis, development, invasion and metastasis of cancerous cells. To efficiently trace living cells in a noninvasive and real-time manner, researchers have devoted much effort to develop new fluorescent probes. Traditional π-conjugated fluorophors are prone to aggregate, which often quenches their light emissions and is a common photophysical phenomenon known as aggregation-caused quenching (ACQ). We succeeded in developing a series of efficient organic emitters with aggregation-induced emission (AIE) characteristics with emission colors from green to far-red/near-infrared by linking propeller-like tetraphenylethene (TPE) or silole unit to traditional dyes through covalent bond. Encapsulation of the AIE luminogens in polymer matrix yields optically stable nanoparticles (NPs) with uniform size, high brightness and low cytotoxicity. The AIE NPs carrying specific functional groups show high emission efficiency, large absorptivity, excellent biocompatibility and strong photo-bleaching resistance, making them ideal for targeting specific cells and/or tissues, and long-term non-invasive in vitro and in vivo cell tracing. The organic AIE dots outperform their counterparts of commercial inorganic quantum dots, opening a new avenue in the development of organic fluorescent probes for following biological processes.

8831-204, Session 1

Colorimetric detection of copper in water using a Schiff base derivative

Diecenia Peralta Dominguez, Mario A. Rodriguez Rivera, Gabriel Ramos-Ortiz, Jose-Luis Maldonado-Rivera, Marco Antonio Meneses-Nava, J. Oracio C. Barbosa G, Ctr. de Investigaciones en Óptica, A.C. (Mexico); Rosa Santillan, Ctr. de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (Mexico); Norberto Farfan, Univ. Nacional Autónoma de México (Mexico)

The synthesis of organic molecules with chemosensors characteristics for detection of heavy metal ions in water is of great importance for environmental applications [1-2]. Organic molecular sensors have the advantage of being used through an easy, fast, economical and reliable optical method for detecting toxic metal ions in our environment. In this work, we present a simple but highly specific organic ligand compound 5-Chloro-2-((E)-((E)-3-(4-(dimethylamino)phenyl)allylidene)amino)phenol (L1) that acts as a colorimetric sensor for ions in a mixture of ACN/H2O (10:1, v:v). Binding interaction between L1 and various metal-ions has been established by UV-Vis spectroscopic measurements that indicate favorable coordination of the ligand with selective metal ions, particularly, with cupper. These results showed that the electronic transition band shape of L1 (receptor compound) change after binding with Cu2+ in aqueous solution. L1 exhibited binding-induced color changes from yellow to pink one detected by the naked eye. This new sensor presented 2.5 ? 10-6 M as limit detection, even under the presence of other metal ions.

[1] P. Kaur, et. al., Talanta 83, (2011), 1695–1700.

[2] Fasil A. Abebe, E. Sinn. Tetrahedron Lett. 52, (2011), 5234–5237.

8831-205, Session 2

OLED-based sensing of relative humidity and oxygen

Eeshita Manna, Fadzai Fungura, Weipan Cui, Joseph Shinar, Ruth Shinar, Iowa State Univ. (United States)

We compare the use of standard OLEDs to microcavity OLEDs in sensing applications. Green and UV microcavity OLEDs are used for O2 sensing with detection by P3HT:PCBM- or CuPC/C70-based photodetectors in compact all-organic devices. Blended sensing films are developed to enable the monitoring of the effect of relative humidity on the photoluminescence (PL) decay time of oxygen-sensitive dyes in such specific matrices. IR organic photodetectors for monitoring water content/humidity are also presented.

8831-206, Session 2

Integrated sensors for point of care diagnostics *(Invited Paper)*

John C. de Mello, Imperial College London (United Kingdom)

Microfluidic devices have shown themselves to be highly effective for laboratory-based research, where their superior analytical performance has established them as efficient tools for genetic sequencing, proteomics, and drug discovery. However to date they have not been well suited to point-of-care diagnostic applications, where cost and portability are of primary concern. Although the microfluidic chips themselves are cheap and small, they must generally be used in conjunction with bulky optical detectors, which are needed to identify or quantify the analytes or reagents present. Here we report the use of miniature on-chip light sources and photodetectors based on light-emitting polymers, together with a range of new low cost strategies for the sensitive detection of low concentration analytes.

8831-207, Session 2

Organic optoelectronic sensors for security and medical applications *(Invited Paper)*

Ifor D. W. Samuel, Yue Wang, Univ. of St. Andrews (United Kingdom); Alexander L. Kanibolotsky, Peter J. Skabara, Univ. of Strathclyde (United Kingdom); Ashu K. Bansal, Mario E. Giardini, Graham A. Turnbull, Univ. of St. Andrews (United Kingdom)

Organic semiconductors are of considerable interest for a wide range of sensing applications. This talk will present recent advances in two domains of sensing. The first part concerns the use of organic semiconductor lasers for sensing explosive vapour. We have investigated a range of organic semiconductors for this application and compare and contrast their properties. In particular we find that truxenes provide very attractive properties for explosive vapour sensing. The second domain of sensing that we report is a muscle contraction sensor. This device measures changes in muscle optical properties under either isometric or isotonic contraction.

8831-208, Session 2

Fluorescent protein-based photonic devices *(Invited Paper)*

Malte C. Gather, Technische Univ. Dresden (Germany) and Massachusetts General Hospital (United States) and Harvard Medical School (United States)

The discovery and development of fluorescent proteins represents a major breakthrough for biomedical research and has enabled non-destructive monitoring and imaging of various biological processes in-vivo. Based on our recent finding that the green fluorescent protein, GFP, can not only serve as a fluorescent probe but is also capable of generating stimulated emission in an efficient manner, we discuss possibilities to use fluorescent protein-based cell lasers and other protein based devices as sensors. In particular, we will discuss the properties of these proteins in the solid state and demonstrate lasing and sensing applications based on solid state protein devices.

8831-227, Session PWed

Triphenylamine and naphthalimide derivatives for optoelectronic applications

Saulius Jursenas, Arunas Miasojedovas, Vygintas Jankauskas, Vilnius Univ. (Lithuania); Gjergji Sini, Univ. de Cergy-Pontoise (France); Dalius Gudeika, Asta Michaleviciute, Ramunas Lygaitis, Saulius Grigalevicius, Juozas V. Grazulevicius, Kaunas Univ. of Technology (Lithuania)

Organic electroactive molecules having both donor and acceptor substituents are of increasing importance for the application in optoelectronic devices such as bulk heterojunction solar cells and sensors.

1,8-naphthalimide derivatives represent an attractive class of electron-deficient organic materials with high electron affinities. They have wide energy gaps and low reduction potentials. Organic molecules containing triphenylamine units are of significant importance among the solution-processable amorphous organic molecular materials, and have been intensively investigated for the applications in optoelectronic devices. These derivatives show pronounced hole transporting ability.

In this work photophysical properties of a series of novel solution-processable 1,8-naphthalimide derivatives with triphenylamine fragment as core have been investigated. The compounds was found to show ambipolar charge transport with electron mobility values up to 7.5?10^-4 cm2/Vs at an electric field of 1?106 V/cm. The optical and electrical properties of the compounds are rationalized by density functional theory modeling. The impact of polar groups and the number of naphthalimide arms on optical end electrical properties of the compounds is discussed. The compounds show efficient fluorescence (up to 78%) and pronounced positive solvatochromic effect in wide range of 400-730 nm with reasonable fluorescence efficiency. The compounds embedded in a transparent polystyrene matrix as temperature-time fluorescence sensors exhibit reverse color changes upon annealing.

8831-228, Session PWed

Stimuli responsive poly-N-isopropylacrylamide - phenylene vinylene oligomer conjugate

Young Il Park, Bingqi Zhang, Cheng-Yu Kuo, Jennifer S. Martinez, Hsing-Lin Wang, Los Alamos National Lab. (United States)

Phenylene vinylene trimer (OPV) and PNIPAM conjugate with stimuli responsive optical properties has been synthesized through formation of amide linkage between PNIPAM and carboxylic acid terminated OPV. This material exhibits thermoresponsive optical properties as temperature exceeds lower critical solution temperature (LCST), which is 32 oC for PNIPAM and the conjugate. This PNIPAM-trimer conjugate is fully characterized by using NMR, FT-IR, temperature-dependent UV-Vis and fluorescence spectroscopy. We have found the polymer conjugate solution turns opaque as temperature exceeds LCST and a five-fold increase in quantum yield (QY) as temperature increases from 20 oC to 70 oC. Such distinct increase in QY is likely due to the rigidchromism; i.e., change in optical properties due to confinement of the chromophores resulting from restriction of polymer conformational structures. The PNIPAM-trimer conjugate also show decrease in decay life time with increasing temperature, while OPV trimer alone shows no change in decay life time as a function of temperature. These unique optical properties are not observed in trimer and PNIPAM mixture, suggesting the stimuli responsive optical properties can only occur in PNIPAM/trimer conjugate linked through covalent bond.

8831-229, Session PWed

An implantable PVDF microphone for the totally implantable cochlear implant

Andy Zhang, Elizabeth Olson, Ioannis Kymissis, Columbia Univ. (United States)

A cochlear implant (CI) is a semi-implantable prosthesis that partially restores hearing by electrically stimulating the hearing nerves in the inner ear. A major advance for the future would be a totally implantable prosthesis, where all the external components of the current CI device are implanted under the skin. To achieve this, one of the major challenges is to develop an implantable acoustic sensor to replace the external microphone currently used with CIs.

In this paper, we report on the development of a piezoelectric polymer microphone, which is designed to be implanted in the inner ear to pick up the sound pressure in the cochlear fluid. A significant advantage of such a microphone placement is that it includes the outer and middle ears as part of the sound pick-up. The outer and middle ears function normally in most CI recipients, but are totally bypassed in the current CI devices. To study this novel concept, we designed a proof-of-principle prototype, which is based on the micro-fabrication processing of PVDF polymer films. The PVDF film is both the device substrate and the piezoelectric material of the microphone. This poster will demonstrate the scaled prototype and an evaluation of the performance and feasibility of the design concept.

8831-230, Session PWed

Potential application of organic self-assembled monolayers to TiO2-based photodetectors

Chun-Pei Cho, National Chi Nan Univ. (Taiwan)

Monitor of UV radiation is an ongoing research topic to develop UV photodetectors with a device structure very similar to dye sensitized solar cells (DSSC) consisting of nanocrystalline TiO_2. With a wide band gap, TiO_2 is inherently UV selective [1]. It has been demonstrated that porous TiO_2 nanostructures improve photoresponsivity owing to the light scattering effect which enhances light harvesting efficiency [2]. Therefore, the nanoporous TiO_2 electrode utilized in DSSCs can also be applied to fabricate TiO_2 photodetectors. It has been known that the photoresponse of a TiO_2 photodetector largely depends on its energy band gap. Moreover, the responsivity is increased by reducing Schottky barrier at TiO_2 interface [3]. So the concept of tuning energy barriers, which has already been employed in organic electronic devices using self-assembled monolayers, has potential application to TiO_2 photodetectors [4,5]. As the approach we modified the TiO_2 photoelectrodes for DSSCs, phosphonic acids with various terminal groups and chain lengths can be selected to form dipole layers on TiO_2 surface to investigate how the modifications affect the open-circuit voltages (Voc), leakage currents, electron lifetime, charge recombination, response times and external quantum efficiency, etc., of the photodetectors made of nanoporous TiO_2. When a phosphonic acid with a negative dipole moment is used, the conduction band bottom (ECB) of TiO_2 shifts closer to the vacuum level. This could cause a larger Voc, suppression of charge recombination and leakage current, and probably a higher photoresponsivity. It has been demonstrated that Voc is dipole-related, indicating that the performance of a TiO_2 photodetector could be improved if a phosphonic dipole layer appropriately alters the energy band gap of TiO_2 and the Schottky barrier at TiO_2 interface. The I-V curves, photoelectrochemical parameters and electrochemical impedance spectra have been measured for further discussion and explanations.

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8831-209, Session 3

Organic field-effect transistors and organic diode structures for ion-detecting sensor elements in aqueous environment *(Invited Paper)*

Emil J. W. List, Technische Univ. Graz (Austria) and NanoTecCenter Weiz Forschungsgesellschaft mbH (Austria)

Organic field-effect transistors (OFETs) are highly promising candidates for chemical and biological sensing. Many organic compounds are solution-processable at low temperatures on a variety of substrates, which allows for cost-effective fabrication methods, leading to smart (disposable) sensor tags in the field of health-, food- and environmental monitoring. Concerning the detection of ions or biological molecules in aqueous solutions, a water-stable operation of OFET sensor elements is crucial. Thus low voltage operation is a prerequisite.

In this context electrolyte-gated OFETs (EGOFETs) seem to be the devices of choice. Due to the formation of an electric double layer at the electrolyte/organic semiconductor interface, they exhibit a very high capacitance allowing for a low voltage operation. Moreover, it was reported that devices are stable even if the organic semiconductor is in direct contact with water. Since these transistors are very sensitive to changes of the interface potential they constitute ideal candidates as transducers for potentiometric ion sensors.

Here the realization of ion-selective EGOFETs is discussed. In this context the device stability of poly(3-hexylthiophene) (P3HT) – based EGOFETs on various substrates gated using water and different concentrations of NaCl in water are presented. In order to obtain a sensitive as well as selective response to sodium a commercial available ion selective membrane was introduced and the corresponding interfaces as well as the limiting factors of this ion sensor concept were investigated. The applicability of the sensor is tested in ambient conditions using a broad variety of analytes with and without interfering ions (e.g. different mineral waters).

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8831-210, Session 3

Electrostatically coupled chemical sensors based on organic semiconductors *(Invited Paper)*

Ananth Dodabalapur, Davianne Duarte, Barrett C. Worley, Bradley J. Holliday, The Univ. of Texas at Austin (United States)

Recently, we proposed and demonstrated sensors based upon the 4-terminal coupled field-effect transistor sensor concept. These sensors employ electrostatically coupled channels: one channel is typically a chemically sensitive organic semiconductor and the second is silicon. This architecture effectively combines the demonstrated chemical sensitivity and selectivity of organic semiconductors (which can be further enhanced through the use of suitable receptors) and the sensitivity and robustness of silicon technology. Such sensors were found to be very sensitive – considerably more so than equivalent three terminal organic field-effect transistor sensors. In this presentation we compare such sensors with a new type of coupled sensor that we have proposed: an electrostatically coupled chemiresistor and field-effect sensor. This new type of sensor is two sensors in one: the chemiresistor sensor (with appropriate receptors) is exposed to the sensing ambient and the capacitively coupled Si transistor channel is sensitive to dipoles induced by analyte molecules interacting with receptors. This large dipole moment can trap charges in the organic chemiresistive layer leading to threshold voltage shifts in the silicon channel. We will also describe a model and experimental procedures we have developed to select suitable receptor molecules.

8831-211, Session 3

Printed, low voltage electrolyte gated transistors and circuits *(Invited Paper)*

C. Daniel Frisbie, Univ. of Minnesota (United States)

By virtue of their enormous gate capacitance, electrolyte gated transistors (EGTs) can operate at supply biases as low as 1 V which makes them interesting devices for application as wearable potentiometric or amperometric biosensors. This talk will review the current performance of p-type and n-type EGTs and discuss their fabrication using printing methods. Specific device metrics that will be covered include ON/OFF current ratio, threshold voltage, carrier mobility, stage delay time, and operational stability. Simple EGT demonstrator circuits and sensing applications will also be discussed.

8831-212, Session 3

Flexible organic active matrix amplifier system for biomedical applications *(Invited Paper)*

Tsuyoshi Sekitani, Tomoyuki Yokota, The Univ. of Tokyo (Japan)

We demonstrate the fabrication of a large-area flexible strain-sensing system consisting of a two-dimensional array of organic self-bias-feedback amplifier cells with signal gain of 400 by integrating 2-V operational organic pseudo-CMOS inverters self-bias amplifier system with polymeric piezoelectric (PVDF) sheet. The amplifier system consists of a self-assembled monolayer (SAM) capacitor matrix sheet, two-dimensional array of organic pseudo-CMOS inverter with floating gate structure sheet and an active matrix of organic field effect transistors sheet. The amplifier sheet comprises 8 ? 8 amplifier cells with an effective size of 7 ? 7 cm2. The organic transistors exhibit mobility of 1.7 cm2/Vs in the saturation regime. When we touch the cell of PVDF sheet (mechanical pressure is applied), the small signal is generated by intermolecular polarization in the PVDF. These signals are amplified by organic amplifier circuits from 10 mV to 150 mV.

A 2D array of organic amplifiers (active matrix amplifier system) was fabricated directly on a 75-?m-thick flexible polyimide substrate. The amplifier was fabricated using an inverter with a pseudo-CMOS layout comprising four p-channel organic transistors. The flexible, p-type channel was formed using dinaphtho[2,3-b:2?,3?-f]thieno[3,2-b]thiophene (DNTT), and gate dielectrics were formed with 4-nm-thick aluminum-oxide and a 2-nm-thick self-assembled monolayer. The manufactured transistor active matrix is encapsulated within a 2-?m-thick parylene by chemical vapor deposition. to serve as a passivation layer and as an overcoat layer for enhancing mechanical flexibility and durability. Proposed organic transistors and circuits exhibited excellent thermal stability and no degradations were observed even after 121 oC for 20 min.

8831-213, Session 3

OECT based devices for monitoring dynamics of bio-relevant molecules and nano-systems towards biomedical applications and drug delivery

Giuseppe Tarabella, Agostino Romeo, Nicola Coppedè, Pasquale D'Angelo, Roberto Mosca, Consiglio Nazionale delle Ricerche (Italy); Roberta Alfieri, Univ. degli Studi di Parma (Italy); Alessandro Pezzella, Marco d'Ischia, Univ. degli Studi di Napoli Federico II (Italy); Pier Giorgio Petronini, Univ. degli Studi di Parma (Italy); Salvatore Iannotta, Consiglio Nazionale delle Ricerche (Italy)

Among the most promising OTFT biosensors devices, Organic Electrochemical Transistors (OECTs) based on conductive polymers have been successfully applied for sensing and monitoring bioelements in liquids environment with high sensitivity. We have recently demonstrated the ability of OECT to be very sensitive to different kind of pharmacophores relevant for nanomedicine and drug delivery area, such liposomal structures and functionalized nanoparticles, with very high sensitivity and real-time capabilities. Normal and cancer cells have been cultivated directly on the OECT channel and the cellular response induced by drugs and other chemical substances has been monitored in real-time. As an interesting e-textile application, we have realized an OECT integrated in a single cotton fiber able to detect saline concentration directly in real sweat, the device being easily integrable with garments. We have recently exploited OECT as a very sensitive device to monitor eumelanin-type biopolymers in colloidal suspension, showing the great versatility of conductive polymer and the first evidence of OECT response to insoluble materials. Here, we propose for the first time OECT as a tool for the analysis of redox properties of phase-responsive eumelanin biopolymers, providing direct proof of solid state quinone-hydroquinone exchange under conditions of relevance for bioorganic electronics.

8831-214, Session 4

Progresses in organic electrochemical transistors *(Invited Paper)*

Fabio Cicoira, Ecole Polytechnique de Montréal (Canada)

Organic electroactive materials have recently been introduced in bioelectronics, where electronic signals are translated into ionic bio signals. An example of organic bioelectronic device is the organic electrochemical transistor (OECT). OECTs are used as sensors for glucose, dopamine, cells and bacteria as well as tools to investigate electronic/ionic transport in conducting polymers. OECTs consist of an organic channel (a thin film of a conducting polymer) in ionic contact with a gate electrode via an electrolyte solution. Typically, a positive potential is applied at the gate electrode, which causes cations from the electrolyte to enter the conducting polymer film and dedope it, causing a switching from an oxidized to a reduced state, which results in a decrease of the transistor current. Although OECTs are increasingly used as bioelectronics devices, their operating mechanism is largely unknown, which limits their use in bioelectronics.

Most OECTs are based on the conducting polymer poly 3,4 ethylenedioxithiophene doped with polystyrenesulfonate (PEDOT:PSS), a hole conducting polymer. In PEDOT:PSS the dopant anions (PSS-) are essentially immobile, since they are part of a polymer chain. Therefore the OECT current modulation is controlled mainly by incorporation of electrolyte cations. To study the effect of the different dopant ions, we used PEDOT with non polymeric dopants, obtained by in situ electrochemical polymerization of EDOT in presence of PF6-, BF4-, ClO4-. In PEDOT doped with non polymeric dopants the ions can be released during dedoping, therefore the dedoping process depends on both cation incorporation and anion release. Electrochemical anodic polymerization of 3,4-ethylenedioxythiophene (EDOT) containing different dopant anions was carried out in presence of a supporting electrolyte containing the dopant (e.g. tetrabutylammonium hexafluorophosphate, tetrabutylammonium perchlorate etc.). To study the effect of the electrolyte ions, various cationic surfactants, with different critical micelle concentration and chemical structure, have been used.

8831-215, Session 4

A transparent organic cell stimulator and sensing transistor for bidirectional communication with primary neurons *(Invited Paper)*

Valentina Benfenati, Stefano Toffanin, Simone Bonetti, Istituto per lo Studio dei Materiali Nanostrutturati (Italy); Assunta Pistone, Istituto per la Sintesi Organica e la Fotoreattività (Italy); Guido Turatti, E.T.C. S.r.L (Italy); Michela Chiappalone, Istituto Italiano di Tecnologia (Italy); Anna Sagnella, Istituto per la Sintesi Organica e la Fotoreattività (Italy); Andrea Stefani, E.T.C. S.r.L (Italy); Davide Saguatti, Giampiero Ruani, Istituto per lo Studio dei Materiali Nanostrutturati (Italy); Roberto Zamboni, Istituto per la Sintesi Organica e la Fotoreattività (Italy); Michele Muccini, Istituto per lo Studio dei Materiali Nanostrutturati (Italy) and E.T.C. S.r.L. (Italy)

The development of advanced biomedical devices capable of real-time stimulation and recording of neural cells bioelectrical activity is a demand to improve our understanding of the functional mechanisms of the Nervous System and the need for effective in vitro drug screening targeted to neuropathophysiologies.

Organic semiconductor materials which combine long-term biocompatibility and mechanical flexibility are suitable candidates for neural cell interfacing. Here, we report on transparent Organic Cell Stimulating and Sensing Transistors (O-CSTs) that provide bidirectional stimulation and recording of primary neurons. We demonstrate that the device enables depolarization and hyperpolarization of primary neurons membrane potential. The transparency of the device also allows the optical imaging of the modulation of the neuron bioelectrical activity. The O-CST device enable extracellular recording with maximal amplitude-to-noise ratio 16 times better than a micro electrode array (MEA) system on the same neuronal preparation. Our organic cell stimulating and sensing device paves the way to a new generation of devices for stimulation, manipulation and recording of neural cell bioelectrical activity in vitro and in vivo.

8831-216, Session 4

Polymer-based artificial retinal prosthesis *(Invited Paper)*

Maria Rosa Antognazza, Diego Ghezzi, Sebastiano Bellani, Nicola Martino, Istituto Italiano di Tecnologia (Italy); Maurizio Mete, Grazia Pertile, Ospedale Sacro Cuore Don Calabria (Italy); Silvia Bisti, Univ. degli Studi dell'Aquila (Italy); Fabio Benfenati, Guglielmo Lanzani, Istituto Italiano di Tecnologia (Italy)

Interfacing organic electronics with biological substrates offers new possibilities for biotechnology due to the unique properties exhibited by organic conducting polymers. These polymers have been used for cellular interfaces in several fashions, including cellular scaffolds, neural probes, biosensors and actuators for drug release. Recently, an organic photovoltaic blend has been exploited for neuronal stimulation via a photo-excitation process. Here, we document the novel use of a single-component organic film of poly(3-hexylthiophene) to trigger neuronal firing upon illumination. Moreover, we demonstrate that this bio-organic interface restored light sensitivity to irradiance in the daylight range in explants of rat retinas with light-induced photoreceptor degeneration. Our organic photovoltaic device proved to possess remarkable light-sensitivity, with a threshold and saturation of retinal field potentials and retinal ganglion cells firing within the daylight range of irradiance and a light threshold of approximately 3 orders of magnitude below the ocular safety limit for continuous exposure to visible light. In addition to this indispensable feature, the organic photovoltaic interface has many potential advantages over previously proposed devices for in-vivo applications, including biocompatibility, no need of external bias, negligible heat generation, and high spatial and temporal resolution in response to pulsed illumination. These findings broaden the possibility of developing a new generation of fully organic prosthetic devices for sub-retinal implants that exploit the unique properties of the polymer interface and its inherent sensitivity to irradiances compatible with physiological levels of illumination. Possibility of subretinal implantation of organic-based artificial prosthesis will be finally presented and critically evaluated.

8831-217, Session 4

H+ and OH-: complementary proton wires in biological proton semiconductors *(Invited Paper)*

Marco Rolandi, Univ. of Washington (United States)

The quest for smaller and faster computing has focused on controlling the flow of electrons and holes in nanoscale molecular structures. In living systems, protonic and ionic currents are the basis for all information processing. As such, artificial devices based on protonic and ionic currents offer an exciting opportunity for bionanoelectronics. Proton transport in nature is important for ATP oxidative phosphorylation, the HVCN1 voltage gated proton channel, light activated proton pumping in bacteriorhodopsin, and the proton conducting single water file of the antibiotic gramicidin. In these systems, protons move along hydrogen bond networks formed by water and the hydrated biomolecules (proton wires). Along these wires, protons hop according to the Grotthuss mechanism. Here, I will draw an analogy between the Grotthuss proton transport and electronic semi conductivity. Acids are described as H+ donors and bases are described as H+ acceptors. These functional groups yield H+ and OH- (proton hole) conducting devices in parallel with n-type and p-type electronic semiconductors. Results from H+-OH- junctions and complementary H+-FETs will be discussed in light of this description. In turn, insights from these devices may be used to see proton transport in biological systems from an alternate perspective.

8831-218, Session 4

Biocompatible electro-ionic signal transduction for bioelectronic interfaces *(Invited Paper)*

Paul Meredith, The Univ. of Queensland (Australia); Albertus B. Mostert, Lancaster Univ. (United Kingdom); Graeme R. Hanson, Kristen Tandy, The Univ. of Queensland (Australia)

An essential element of bioelectronics is the interfacing of conventional electrical control circuitry with a biological entity to read or write information. This poses two particular challenges: i) even the most apparently benign inorganic semiconductors such as silicon have biocompatibility issues; and ii) electrical signals in biological systems are dominated by ion and proton flows, chemical potential gradients, etc. whilst semiconductors are intrinsically "electronic", i.e. current flow is via electrons and holes. This latter requirement means that ion-to-electron (or vice versa) transduction is often required across the in-vivo-ex vivo interface [1].

In my talk, I will address these specific issues and discuss materials and architectures which potentially could allow biocompatible electro-ionic transduction. I will review recent progress and challenges in areas such as proton transistors ("protonics") [2], ionic bipolar junction transistors [3] and hybrid ionic-electronic conductors. Furthermore, I will explore the rather exotic solid-state transport physics at play in naturally occurring biomacromolecules that display hybrid electrical behaviour when partially

hydrated. These materials have significant potential for addressing both the biocompatibility and transduction challenges in bioelectronic interfaces [4].

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8831-219, Session 4

Bio-organic interfaces for cellular photo-excitation

Nicola Martino, Istituto Italiano di Tecnologia (Italy) and Politecnico di Milano (Italy); Maria Rosa Antognazza, Diego Ghezzi, Fabio Benfenati, Istituto Italiano di Tecnologia (Italy); Guglielmo Lanzani, Istituto Italiano di Tecnologia (Italy) and Politecnico di Milano (Italy)

The most common strategies to control electrical activity in living cells are based on electrical or chemical stimulation. However, in recent years, techniques relying on optical stimuli are emerging as promising alternatives with peculiar advantages, particularly for the high degree of temporal and spatial resolution that can be achieved. Here we describe the technique of cell stimulation by polymer photo-excitation (CSP), which takes advantage of the unique optoelectronic properties of the interface between organic semiconducting thin films and an ionic liquid environment. Due to their intrinsic bio-affinity with biological systems, conjugated polymers have been demonstrated as functional substrates for the growth of different types of cellular systems. CSP exploits their ability to generate electrical stimuli following photoexcitation. In particular, we demonstrate that thin films of poly(3-hexylthiophene) (P3HT) are able to elicit electrical activity in different types of cells, from primary neurons to cellular lines. An interesting result is that the stimulation is equally effective with films obtained by blending the donor polymer with an electron acceptor, but also with single component P3HT layers; this allows us to shed light on the actual photoexcitation mechanism, which is based on a capacitive coupling of the active interface with the cellular membrane, as corroborated by further physico-chemical analysis. Other developments of the technique with important consequences for neuroscientific experimentation will also be presented. These results open the way to a new generation of neuronal communication and photo-manipulation tools.

8831-220, Session 5

Infrared photodetectors from all solution-processed inorganic semiconductors *(Invited Paper)*

Jesse R. Manders, Tzung-Han Lai, Jae Woong Lee, Franky So, Univ. of Florida (United States)

Infrared (IR) detection systems are widely used in optical communications, security, ranging, and household electronics. Due to the proliferation of IR-sensitive systems in modern society, high quality photodetectors made from inexpensive and high throughput manufacturing techniques are constantly in demand. Currently, many of the most popular IR photodetectors in use are grown by epitaxial deposition techniques, which are costly and only allow for small area device fabrication. To circumvent the drawbacks of current manufacturing technology, we demonstrate a novel infrared photodetector with tunable absorption spectra by employing all solution-processed inorganic materials. Specifically, quantum dots (QDs) made from lead chalcogenides are used as the IR-absorbing layer, while wide bandgap solution-processed metal oxides are used as the p-type and n-type charge blocking layers in a P-I-N configuration. The absorption spectrum of the IR-active QDs can be tuned throughout a wide swath of the NIR spectrum. Devices have an attractive peak external quantum efficiency (EQE) above 25% and peak responsivity above 0.2 A/W at -1V, comparable to commercially available detectors. Special attention is given to noise levels and frequency-dependent performance of the photodetectors.

8831-221, Session 5

Photoinduced hole-transfer dynamics in organic photodiodes: effects of nanoscale bulk-hetrojunction morphology

Soohwan Sul, Kwang-Hee Lee, Jong-Bong Park, Changhoon Jung, Kyu-Sik Kim, Hyouksoo Han, Samsung Advanced Institute of Technology (Korea, Republic of)

Photo-induced hole transfer dynamics of organic bulk-heterojunction (BHJ) films with different nanoscale morphology is investigated using femtosecond transient absorption (TA) spectroscopy. The BHJ films are composed of N,N'-dimethyl-quinacridone (DMQA) as a donor and a dicyanovinyl terthiophene derivative (DCV3T) as an acceptor, which makes highly efficient green-sensitive organic photodiode (OPD) for image sensor applications. Selective excitations of DCV3T or DMQA/DCV3T in the BHJ films in TA study reveal that charge photogeneration occurs mainly through hole transfer at a donor-acceptor interface and the rate of hole transfer from DCV3T to DMQA depends on the exciton lifetime (1/e-lifetime: ca. 40 ps) and domain size of DCV3T. Hole transfer occurs efficiently with decreasing DCV3T concentration from 75% to 25%, because the domain size decreases and the ratio of interface to bulk increases. On the basis of the charge transfer rate and diffusion length of DCV3T, we estimate the average domain sizes in the BHJ films. For a 50%:50% DMQA:DCV3T blend, the domain size is comparable to DCV3T exciton diffusion length of 5-7 nm. This blend morphology obtained from charge transfer dynamics is compared to the nanoscale morphology obtained from atomic force microscopy and transmission electron microscopy techniques. These results on initial charge transfer rate, recombination, charge photogeneration efficiency, and nanoscale morphology are further discussed in relationship with OPD device performances in terms of charge transport and bias-dependent external quantum efficiency.

8831-222, Session 5

High-gain, low-noise, large linear dynamic range UV hybrid photodetectors enabled by the interfacial trapped charge controlled charge injection *(Invited Paper)*

Jinsong Huang, Fawen Guo, Univ. of Nebraska-Lincoln (United States)

Very weak UV light detection is critically important for defense, air space, radiation sensing applications. Single photon level detection needs UV photodetectors with high gain and low noise. Here, we report a low-cost UV hybrid photodetector which has a huge internal gain of 4,100 under low bias less than 10 volts, enabled by the interfacial trapped charge controlled charge injection. The active materials are organic semiconductors, such as fullerenes, which have strong absorption in UV range. The insertion of buffer layer which composes crosslinked polymer with zinc-oxide nanocrystals simultaneously harvest the high gain as well as the low noise current of the organic photodetector. Strikingly, the noise of the fullerene photodetector with buffer layer was reduced to 7~10 fA Hz-0.5. This low noise was measured directly with lock-in amplifier SR 830, and is approaching the thermal noise limit of 6 fA Hz-

0.5. The combination of low noise and high gain in these photodetectors resulted in a very large specific detectivity of 4?10^15 Jones, which is 2-3 times larger than that of commercial available best silicon and GaN photodetectors in the same spectrum range. Strikingly again, these photodetectors have a super large linear dynamic range in excess of 120 dB under light intensity between 10 fW/cm2~100 mW/cm2, better than any reported solid state photodetectors.

8831-223, Session 5

Integration of transmissible organic electronic devices for sensor application

(Invited Paper)

Furong Zhu, Hoi Lam Tam, Hong Kong Baptist Univ. (Hong Kong, China); Xizu Wang, A*STAR Institute of Materials Research and Engineering (Singapore)

Organic electronics are gradually revealing potential for application in emissive displays, energy generation and optical detection. In this work, we propose a proximity sensor based on the monolithic integration of a semitransparent organic photodetector (OPD), and an organic light-emitting diode (OLED). In the sensor, a thin plasma-polymerized fluorocarbon modified thin silver interlayer is used to connect the front semitransparent OPD and the rear OLED unit. The OPD, possessing strong directional transmission characteristics, acts as an optical coupling layer which enables the enhanced emission from the OLED unit. In addition, it also allows high absorption when light is reflected back from the object. The sensor device has different photo-responses to various types of surfaces, for example, different colored papers and metal foils. Therefore, it can be widely used in the application of planar photo-detectors, imager scanners and proximity sensors.

8831-224, Session 6

Low dark current small molecule organic photodetectors with inverted geometry for hybrid CMOS image sensor applications

(Invited Paper)

Dong-Seok Leem, Kwang-Hee Lee, Kyung-Bae Park, Seon-Jeong Lim, Jung Woo Kim, Yong Wan Jin, Sangyoon Lee, Kyu-Sik Kim, Samsung Advanced Institute of Technology (Korea, Republic of)

Small molecule-based organic photodetectors (OPDs) that are orthogonally photosensitive to different wavelengths of light with R/G/B colors have recently emerged as an alternative to conventional Si-PDs. This enables us to vertically stack the unit R/G/B OPDs in the absence of additional color separation filters, which realise compact, lightweight, and high resolution full color image sensors. In this presentation, we demonstrate high performance green light sensitive OPDs especially with an inverted structure for hybrid CMOS image sensor applications. The inverted geometry i.e., the structure suitable for extracting electrons instead of holes to the bottom electrode of OPDs can provide a good compatibility with conventional CMOS circuits with the characteristic of the electron storage.

Inverted OPDs were fabricated on ITO bottom electrode comprising small molecule organic bulk hetero-junction structures mixed with N,N-dimethylquinacridone (donor) and dicyanovinyl-substituted terthiophene derivative (acceptor), bis-4,6-(3,5-di-3-pyridylphenyl)-2-methylpyrimidine-based charge blocking layer, and a reflective Al top electrode, which exhibited extremely low dark current densities in the range of 1.6-5.4 nA/cm2 at a reverse bias of 3V, high external quantum efficiencies of 55-56% at 540 nm wavelength, and consequently high specific detectivities over 5 ? 10^12 cmHz0.5/W. An additional analysis of 3V-driven OPDs showed the relatively fast photo-response time less than 5 us at cut-off frequency of 70 kHz. Further investigation and characterisation on semi-transparent inverted OPDs by incorporating a thin Ag top electrode will be described in detail for the feasibility of hybrid CMOS imagers.

8831-225, Session 6

Flexible imaging sensors with end application towards x-ray imaging

Abhishek Kumar, Holst Ctr. (Netherlands)

We demonstrate organic imaging sensor arrays on flexible foil fabricated with the solution processing route for both photodiodes and TFTs. We used the photovoltaic P3HT:PCBM blend for fabricating the photodiodes using spin coating and pentacene as semiconductor material for the TFTs. Photodiodes fabricated with P3HT:PCBM are known to have absorption peak in the green light which matches with the typical scintillator output wavelength. The arrays consist of 32x32 pixels with variation in pixel resolution of 200umx200um and of 1mmx1mm. The accurate reproducibility of shadow images of the objects demonstrates excellent potential of these arrays for imaging purpose. We also demonstrate that the crosstalk is insignificant despite the fact that the photodiodes are non-patterned and forms a continuous layer in the array. The semi-transparent top electrode is also a continuous layer above the photodiodes in the array. Further on top we used a thin flexible barrier layer to encapsulate the whole stack to protect from degradation. Since both photodiodes and TFTs are made of organic material, they are processed at low temperatures below 150° C on foil which means that these imaging sensors can be flexible, light weight and low cost when compared to conventional amorphous silicon based imaging sensors on rigid substrates. Further by combining with a scintillator layer on top of the arrays, we show the potential of these arrays for the X-ray imaging application.

8831-226, Session 6

PyzoFlex: a printed piezoelectric pressure sensing foil for human machine interfaces

(Invited Paper)

Martin Zirkl, Gregor Scheipl, Barbara Stadlober, Paul Hartmann, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Michael Haller, Christian Rendl, Patrick Greindl, Univ. of Applied Sciences Upper Austria (Austria)

Ferroelectric material supports both pyro- and piezoelectric effects that can be used for sensing pressures on large, bended surfaces. We present PyzoFlex®, a pressure-sensing input device that is based on a ferroelectric material. It is constructed with a sandwich structure of four layers that can be printed easily on any material. The foil is bendable, energy-efficient, and it can be produced easily in a printing process (Screen Printing or Roll to Roll). Even a pyroelectric hovering mode is feasible due to its pyro electric effect.

The printed energy autarkic sensors serve as a pressure sensitive user interface enabling for pressure and location sensitive multi touch input. Different routines for elimination of cross talk (iteration, prediction, transport matrix) caused by Kirchhoffs´ law have been exploited and true multi-touch input can be achieved by implementing them into a visualization software of the organic sensor array.

Since ferroelectric sensors are not capable of monitoring static conditions, absolute/static pressure levels can be calculated by knowing the potential function of the sensor systems discharge. By that every upcoming sensor value can be predicted and every deviation from that prediction can be addressed to a predictable change of the static conditions. Finally pressure sensitive gesture detection can be realised by a smart sensor design supported by software interpolation and blob detection. An additional benefit is the possibility of printing a semi-transparent (ITO free) touch interface by using PEDOT electrodes.

The superior sensor performance related to stability, sensitivity, linearity and flexibility is demonstrated.

8832-2, Session 1

A method of comparing the speed of starlight and the speed of light from a terrestrial source

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The speed of light is an important physical parameter. Currently it is a common belief of the constance of the speed of light regardless of the relative velocity between the source and the observer. Because the speed of light is very fast, if the relative velocity is small compared with the speed of light, it is difficult to detect the effect of the relative velocity on the measurement of the speed of light. In this paper we present a method of comparing the speeds of starlight and the light emitting from a terrestrial source. We use a telescope to collect the light from the star having significant relative velocity with respect to the earth, e.g. Capella. Then we modulate the starlight and the light emitted from the local source into pulses i.e. these pulses leave the modulator simultaneously. After travelling 4.2 km, these pulses are detected by a receiver. If the starlight and the terrestrial light have the same speed, then these pulses must arrive at the receiver at the same time. Our results show that the arrival times of the pulses of starlight are different from that of the local light. For example, the Capella is leaving away from the earth. The Capella pulses arrive later than the local light pulses. It indicates that the speed of Capella starlight is slower than the common believed value, c. The presented method uses one clock and one stick, so the clock synchronization problem and any physical unit transformation can be avoided.

8832-3, Session 1

A quantum oblivious transfer protocol

Abhishek Parakh, Univ. of Nebraska at Omaha (United States)

We propose an all quantum protocol for 1-out-of-2 oblivious transfer. Oblivious transfer is a counter-intuitive cryptographic primitive in which the receiver receives only the information he is authorized for, while the sender does not know what information receiver received. In 1-out-of-2 oblivious transfer, Alice sends two bits to Bob who can choose only one of them to read, while Alice does not know which bit Bob read. The quantum version of oblivious transfer, in the past, unlike the proposed protocol, has only been implemented using a combination of quantum and classical channels. Since it has been shown that it is impossible to build quantum oblivious transfer based on quantum bit commitment protocols, the propose protocol is significant. Further, the protocol is secure if qubits are quanta and cannot be stored, given current technology.

The Protocol: Alice and Bob agree on quantum states |0> and |1> to represent bits 0 and 1, respectively. Further, assume that these states are encoded using photons as qubits. Therefore, Alice encodes the bits she has as qubits X0 and X1. The protocol proceeds as follows:

1) Alice and Bob choose secret random transformations Ua and Ub, respectively, such that they commute, UaUb=UbUa.

2) Alice applies her secret transformation to X1 and X2 and sends Bob Ua(X1) and Ua(X2), in order.

3) Bob chooses the qubit he would like to retrieve, say Xb, and sends to Alice UbUa(Xb)=UaUb(Xb).

4) Alice applies the inverse transformation for Ua on the received qubits and sends to Bob Ub(Xb).

5) Bob applies the inverse transformation on the qubit that he receives and retrieves Xb.

We prove the security of the proposed protocol. Further, we discuss the extension of the above protocol to k-out-of-n oblivious transfer and show some possible attacks on it.

8832-4, Session 1

A high-speed GaAs-based electro-optic modulator for polarization, intensity, and phase modulation

Hiroshi Kato, Optelian (Canada); Jeffrey D. Bull, The Univ. of British Columbia (Canada) and Optelian (Canada); Benjamin Tsou, Optelian (Canada); Nicolas F. Jaeger, The Univ. of British Columbia (Canada)

We report on the development of novel electro-optic modulators fabricated on epitaxial layers of aluminum gallium arsenide (AlGaAs), grown on a GaAs substrate. The current device has a unique single waveguide structure combined with travelling wave slow wave electrodes. This design allows for high speed modulation of the polarization state of light with low differential group delay, low optical loss and frequencies of 50 GHz and beyond. The devices are based on TE-TM mode convertors that modulate the state of light from one linear polarization state to an orthogonal linear state passing through elliptical and circular polarization states. Devices can also be configured to modulate the phase or intensity of an optical signal by appropriate alignment of the polarization axis of the input light or by placing a polarizer at the output. Key characteristics and performance metrics of the devices are reported. Applications that use the device for enhancing analog communication links, analog to digital signal conversion and sending keys for encryption are reviewed to illustrate the diverse nature of the systems being developed and which demonstrate the versatility of the ways in which the GaAs mode converter modulator may be used.

8832-5, Session 1

Numerical examination of acousto-optic Bragg interactions for profiled lightwaves using a transfer function formalism

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Recent results from an acousto-optic (AO) Bragg cell under first-order intensity feedback, while satisfactory, are limited notionally by the standard AO assumption of uniform plane waves of light and sound. This highly complex wave-particle problem may simultaneously be described via Maxwell's equations, and also a quantum description whereby the upshifted and downshifted orders of diffracted light are represented by a wave-vector triad consisting of two photons and one phonon. Nominally, for uniform plane waves, the Bragg-diffracted first-order light is a sin2 function versus the optical phase-shift parameter

([alpha]0). An earlier model developed for Gaussian profiled plane waves predicted approximately Gaussian scattered beams distorted at higher Q (Klein-Cook) values. We present here profiled optical plane wave propagation through a Bragg cell, examining the scattered first-order beam from different perspectives. The results from non-uniform plane-wave diffraction indicate at least two counter-intuitive outcomes. First, it is found that even for profiled beams, the first-order light maintains its sin2 characteristic analogous to the uniform plane wave case. This unexpected conformity, however, begins to break down at higher Q-values. This is particularly counter-intuitive, since at higher Qs, one would expect the device to behave more Bragg-like than at lower Qs. This may have implications embedded in the properties of photon scattering by phonons, and might well be an area worthy of further explorations. A second observation in the asymptotic limit [alpha]0 --> [infinity] shows an axial shift of the beam profile in the first order, conforming to wave theory predictions; however, the shift appears to exist only on one side of the radial axis and not the other. This finding is also open to explanations based on possible photon scattering by a Bragg cell under profiled beam diffraction.

8832-6, Session 2

Mechanism of photonic interactions

Andrew Meulenberg Jr., Univ. Sains Malaysia (Malaysia) and Hi Pi Consulting (United States)

The normal mathematical model of light, using the simple summation of sine waves, gives excellent predictive capabilities for light. It predicts the results of the interactions for even the components of light, the photons. However, it cannot provide a valid physical model of their interactions or of the photons themselves. This paper attempts to provide such a model that also fits and explains the known characteristics of light and its interactions. The simplest version of this model assumes that there exists, within a photon, 'sources' that produce the observed and mathematically modeled, transverse electric and magnetic fields. These source terms are not physical entities in the normal sense. They represent concentrations of field lines that, in turn, are only gradients of potentials. The nature and consequence of such sources is explored. A main new feature of this model is the recognition of the role of longitudinal field lines. This is a 'what if', rather than a 'how' and 'why', paper.

8832-7, Session 2

A mechanism for wave interaction during interference

W. R. Hudgins, Hi Pi Consulting (United States); Andrew Meulenberg Jr., Univ. Sains Malaysia (Malaysia) and Hi Pi Consulting (United States)

Waves carry energy, force and momentum. Therefore, colliding wave trains have the physical capacity to interact and do so to form and maintain standing waves. Standing waves form in liquids, gases, electrical circuits, and electromagnetic (EM) waves. Because wave behavior exists, irrespective of media type, we have investigated the possibility that waves in various media do interact and do so through a common, physical mechanism. We propose that standing waves are composed of reverberating segments containing reflection zones (nodes) where potential energy resides and where there is little lateral energy flow and kinetic energy zones where lateral energy flow is maximal.

Considering interference phenomena; interference patterns form when waves collide at an angle. During the collision two force vectors resolve. One is the vector sum of the longitudinal components of the two, converging wave trains. The second is the combination of opposing (colliding), transverse acting forces that will produce a standing wave component. This second component separates the longitudinal, moving waves into parallel zones where energy may be only potential in one zone and kinetic in the next. For example, in the interference pattern formed by converging components of a split laser beam (our zero slit experiment, ZSX), potential energy resides in the dark, longitudinal zones (null zones), kinetic energy in the parallel, bright zones. We have experimental evidence that the colliding forces from two converging laser beams produce a standing wave component that can redirect and concentrate the combined, light energy without the use of lenses.

8832-8, Session 2

Does the coherent lidar optical system corroborate non-interaction of waves (NIW) principle of light?

Narasimha S. Prasad, NASA Langley Research Ctr. (United States); Chandrasekhar Roychoudhuri, Univ. of Connecticut (United States)

NIW (non-interaction of waves) has been proposed by one of the coauthors. The NIW principle states that in the absence of any "obstructing" detectors, all the Huygens-Fresnel secondary wave lets will continue to propagate unhindered and without interacting (interfering) with each other. Since a coherent lidar system incorporates complex behaviors of optical components with different polarizations including circular polarization for the transmitted radiation, then the question arises whether the NIW principle accommodate elliptical polarization of light. Elliptical polarization presumes the summation of orthogonally polarized electric field vectors which contradicts the NIW principle. In this paper, we present working of a coherent lidar system using Jones matrix formulation that the system behavior is congruent with NIW principle. The Jones matrix elements represent the anisotropic dipolar properties of the molecules of the optical components. Accordingly, when we use the Jones matrix methodology to analyze the coherent lidar system, we find that this methodology inherently supports the NIW principle.

8832-9, Session 2

Understanding beam alignment in a coherent lidar system

Narasimha S. Prasad, NASA Langley Research Ctr. (United States); Chandrasekhar Roychoudhuri, Univ. of Connecticut (United States)

Optical beam alignment in a coherent lidar or ladar receiver system plays a critical role in optimizing its performance. Optical alignment in a coherent lidar system dictates the wavefront curvature (phase front and Poynting vector) matching of the local oscillator beam with the incoming receiver beam on a detector. However, this alignment is often not easy to achieve and is rarely perfect. Furthermore, optical fibers are being increasingly used in coherent lidar system receivers for transporting radiation to achieve architectural elegance. The detector response characteristics vary with the misalignment of the two pointing vectors. Misalignment can lead to increase in DC current. Also, a lens in front of the detector may exasperate phase front and Poynting vector mismatch. In this paper, we will analyze the extent of misalignment on the detector specifications using pointing vectors of mixing beams. Our analysis will discuss coherent lidar system receiver performance optimization by considering detector characteristics, difference frequency, fringe motion and oscillatory dc current.

8832-10, Session 3

The photon: issues of integrity *(Invited Paper)*

David L. Andrews, Univ. of East Anglia Norwich (United Kingdom)

Since the arrival of the laser, the distinctive and often paradoxical nature of the photon has become more than ever evident. What the optics community now understands by a 'photon' has become much richer – certainly less simple, than Einstein's original conception. There has been a marked expansion in the pace of development since the now familiar

derivative term 'photonics' first emerged, and in much current theory any dividing line between 'real' and 'virtual' photons proves illusory. If, in this technical sense, no photon can ever be regarded as entirely real, one is drawn to the deeper philosophical question of whether the photon is 'real' in the broader sense of reality. Some consider electromagnetic fields to be closest to irreducible reality. Yet whether fields or photons are the terms in which we elect to describe optical phenomena, neither represents what is actually measured. The surest ground is where theory is cast in terms that explain or predict actual observations, under given conditions. It is consistent with the path integral formulation of quantum mechanics that derivations should not prescribe what intervenes between setup and measurement, but instead allow for all possibilities. One of the beauties of the underlying mathematics is its capacity to home in on possibilities that most closely conform to post-event physical interpretation. For practical purposes, a richly diverse range of phenomena now owe their primary conception to the photon; a strong case can be made that in the modern world, 'photonics' has become more real than the photon.

8832-11, Session 3

"Hidden variables" basically unfolded

Erich H. Berloffa, Leopold-Franzens-Univ. Innsbruck (Austria)

Abstract: "Hidden Variables" in QM are entangled with dipole elongation (a) and linewidth (?). It turned out the quantity a?/? plays a dominant role. Rules of QM transition themself are not questioned. This quantity can be fixed for a "single" transition (no interaction with other atoms or molecules) as well as for an ensemble within a thermal bath, and when developed further unveils details of radiating matter especially when the linewidth of the radiating source is precisely known. In principle a "single" isolated local photon emanated by an adequate quantum transition is not detectable.

Stepping towards non-thermal radiation sources (lasers) quantitative assertions can be made in regard of entanglement respectively the lateral dimension affected by such a process. Moreover, this concept applied to g-radiation reveals inherent linewidths of g-ray transitions requires more than a single elementary charge being involved. A further aspect of this investigation makes it obvious: The Stefan-Boltzmann constant is not natural; in fact it is a composition of the constants of Planck and Boltzmann and the velocity of light as well. Exemplary analyzing a specific hydrogen line in the solar spectrum (l= 486 nm) one must infer from its linewidth data this species shows photon entanglement, or alternatively substantial density fluctuations becomes obvious.

Keywords: Single photons, linewidth, entanglement, dipole elongation due to quantum transition, 2D-density of radiating atomic oscillators, solar photosphere.

8832-12, Session 3

Phat photons and phat lasers

Pharis E. Williams, Consultant (United States)

Einstein's initial prediction, based upon statistical considerations, was that the energy of quanta of light be given by h?. A new theoretical development predicts that photon energies are quantized as N2h?. Such quantization of photon energy changes the character of the photon from the Einstein photon that does not have a quantum number. Photon energy that includes a quantum number means that for a given energy the frequency may have more than one value. Conversely, photons of a given frequency may be found that have more energy than the Einstein photon. Further, the phat photons, all at a given frequency will have energy proportional to the number of phat photons and N^2. For these phat photons the electric field strength, which causes breakdown in optical fibers or air, depends linearly on N. Thus, more energy may be transmitted using phat photons of higher quantum numbers than increasing the number of photons of lesser quantum numbers while still keeping the electric field below the breakdown level. Further, while the stimulated and spontaneous emission probabilities are proportional to 1/N^2 the Rayleigh scattering cross section diminishes by 1/N^8. This reduction in the scattering cross section means that a laser emitting phat photons with N>1 will lose less energy traveling through the Earth's atmosphere than lasers using N=1. This reduction in energy losses through the atmosphere means increased efficiency for Earth based beamed applications.

8832-13, Session 3

Statistics of photon splitting and correlation filtering

Aloysius F. Kracklauer, Private Consultant (Germany)

We describe a possible statical effect capable of testing the widely accepted principle that, "photons cannot be split." This effect depends on the dispersion spectrum; if the photon is split, it will be essentially identical for both output channels of a beam splitter. On the other hand, if the photons are not split, these two distributions will differ by cause of a contribution from statistical effects in the crystal generating the individual pre-split photons. Mathematical analysis showing the consequences of various distributions of arrival time in both the source and detector, indicates that, it may be possible to distinguish split photons from random coincidences.

A possible experiment is described. In addition, the techniques used for the above will be applied to the generation of correlated photon pairs and used to analyze the data analysis algorithms for experiments involving quantum entanglement. Results point to possible non quantum generation of the data patterns currently thought to exclude non quantum clarifications

8832-14, Session 4

New experiments and questions to shed light on the nature of a photon

Carl F. Maes, College of Optical Sciences, The Univ. of Arizona (United States)

Is the nature of light observed only indirectly after its interaction with matter? We currently lack an experimental technique which would isolate the nature of light without the use of matter i.e., a detector.

We will present additional experiments which, although again indirect, may reveal new understandings (but mostly more questions) about the nature of light. This talk will not report research results, but rather be an invitation for others to conduct similar such measurements as will be proposed.

Can atomic recoil upon photo-emission be measured accurately? If so, what information about a photon's can be gained by measurement of the atomic recoil resulting from its emission without disturbing the photon?

What are the photon statistics in a dark fringe?

Is light reflected in the region of a dark fringe by a metal reflector?

8832-15, Session 4

Single-photon detection, truth, and misinterpretation

Erich H. Berloffa, Leopold-Franzens-Univ. Innsbruck (Austria)

In this investigation it is shown that modern photon detectors indeed can resolve the energy of a "single photon" , but this is only due to its tiny active area. From basic solid state physics it can be derived that special doping of semiconductor substartes is necessary for accomplishing this task. The fact we can detect single photon event does not mean that there is a 1:1 relation between the detected event and a corresponding "single" quantum transition. Propagation behaviours have been simply overlooked in the past. Practical examples are demonstrated on hand of a commercial pin-/and AVD photodiode.

8832-16, Session 4

The nature of the photon from viewpoint of a generalized particle mode

Albrecht Giese, Deutsches Elektronen-Synchrotron (Germany)

Particle physics deal about a few basic particle types:

- Leptons
- Quarks
- Photons

Most of the particles we know are leptons or are built by quarks (as e.g. mesons). A special place occupies the photon which seems to be independent. And – among other aspects – it has twice the spin of leptons and quarks.

Using the properties of particles such as their mass, spin, and magnetic moment, and from the relativistic behaviour of matter – which can be derived from the 'zitterbewegung' of the electron – we can draw up a model in which a particle is composed of a pair of sub-particles which orbit each other. This model conforms to the quantum mechanical concepts of Louis de Broglie. It replaces the idea of particle-wave-duality founded by the Copenhagen interpretation of QM. The model allows for a description of particle properties with high precision on the basic of classical physics.

This particle model which was developed for leptons and quarks has to be applied also onto the photon. The consequences for the understanding of the photon are an essential topic of this talk.

This model also has the capability to explain open issues like cosmological inflation, dark energy, and dark matter. And in contrast to the way as Albert Einstein has done it, relativity is not founded on 'principles' but follows from the structure of fields and particles and gets in this way a real physical basis.

8832-17, Session 4

Consequences of partitioning the photon into its electrical and magnetic vectors upon absorption by an electron

Daniel S. Szumski, Independent Scholar (United States)

This research develops a theory that unites in a single equation, the heat radiation theory of Planck and the heat-of-molecular-motion theory of Maxwell and Boltzmann.

Photon absorption is considered a two-step process. The first is an adiabatic reversible step, wherein one-dimensional light energy is absorbed in a quantum amount by an electron. The absorbed quanta is still 1-dimensional(1-D), and remains within the domain of reversible thermodynamics.

Absorption's second step is a dimensional restructuring wherein the electrical and magnetic vectors evolve separately. The 1-D electrical quanta transforms into 3-D electrical charge density, in accordance with the Equi-partition Theorem, and along the axes of the electron's three spatial coordinates. This displacement of the generalized coordinates translates to 3-D motion, the evolution of Joule heat, and irreversibility. The magnetic vector has no 3-D equivalent, and can only transform to 1-D paramagnetic spin. Accordingly, photon de-coupling distorts time's fabric, giving rise to the characteristic spectral emittance.

The new equation shows how non-equilibrium and far-from-equilibrium spectra are described by two temperatures: the thermodynamic temperature of the Rayleigh-Jeans Law, and a new quantity described as the radiation temperature (Wein Displacement Law temperature).

This treatment of photon absorption leads to an alternative understanding of covalent bonds. The author also speculates that the non-equilibrium spectral distribution could be useful in describing the far-from-equilibrium energy storage in living systems.

8832-61, Session PMon

Unification of fundamental interactions of nature

Akbar Rahmani-Nejad, Maharan Engineering Corp. (Iran, Islamic Republic of)

In this paper it is tried to introduce an interaction as the origin of fundamental interactions of nature (electromagnetic , gravitational, strong and weak nuclear forces). this has a distinct formula that by inserting charge in formula , coulomb or electric force is obtained. by inserting moving charge (charge and velocity) in the formula we will reach to magnetic force formalisms plus coloumb constant including faraday law, ampere law, gauss law etc. by inserting mass instead of charge, and considering long ranges and some statistical concepts gravitational force plus universal gravitational constant. by limiting the interaction rate to sub fm ranges, strong nuclear force will be formalized. It is obvious that all three forces of coulomb force, gravitational force and magnetic force on a moving charge all have common shape, all three forces are inversely proportional to square of distance all 3 are proportional to multiplication of charges or masses of two distinct particle or objects. Strong force is the same form of original force but when the distance is under fm due to inverse proportionality to square of distance the energy of the force will be in the range of Mev. Weak nuclear force is not considered to be a force, but just the result of increasing mass and effective interaction distances in respect to strong nuclear forces interaction distance and also in unbalancing nucleon's mass, charge and some other quantum numbers. It is impossible to explain formulas and methods in this brief explanation. But by reaching to the answer, there will be a new interpretation of mass, inertia, close and far interactions, fields, wave, energy, mass, space etc. for example mass will explained of a buckle of energy that space only can contain it in a specific point it (point of space) and two buckles of energy cannot occupy the same point of space. Field is only the direction of possibility of interactions. Space can be divided in two category, infinite and finite. Finite space can hold and interact with particles which have an integer multiplication of their wavelength leading to creation of particles having mass. Other new concepts like space-particle resonance will be introduced. Mass and photons are two distinct orthogonal mathematical-space of energy. All it can be mentioned is that there will be a new approach toward this subject and details can be mentioned in complete paper.

8832-62, Session PMon

A new approach to the concept of double-slit experiment by consideration of each slit as a very short waveguide

Akbar Rahmani-Nejad, Maharan Engineering Corp. (Iran, Islamic Republic of); Ali Rahmani Nejad, Doctor Mosaheb College (Iran, Islamic Republic of); Ahmad Rahmani Nejad, Islamic Azad Univ. (Iran, Islamic Republic of)

In this paper it is proved that by considering of each slit of double slit experiment as a very short millimeter or micrometer waveguide it is possible to reach a very precise explanation of optical beam propagating through slits and constituting modes of propagation – that is very similar to Schrodinger equation – it is possible to have very precise analysis and formulation of this phenomenon. This analysis shows that in the case of diffraction of one slit it is enough to consider that each TE or TM modes diverged after passing through slits, i.e. the shape of fringes will be calculated as precisely as observed in experiments. This will arouse us to have a new verification to Fraunhofer and Fresnel formulations for far field and near field diffractions and Huygens principle as well. On the other hand diverging light beams on output edges of each slit again prods us to have a new consideration to bending of light in the vicinity of matter that it is not necessarily to observe this phenomenon near massive objects as predicted by space curvature interpretation of general relativity.

8832-19, Session 5

Chemical and physical action of solar radiation according to the Gibbs method

Viktor Laptev, Halyna M. Khlyap, State Pedagogical Univ. (Germany)

Corpuscular nature of light (Newton) and wave nature of light (Huygens) is used in in a big number of technical devices where the light beams as electromagnetic waves (Maxwell) transfer quanta of energy (Planck). The particle of light is (according to Einstein) a quantum of the electromagnetic field's energy (Lewis). The laws of thermodynamics are applicable to the light beams as well as to the photonic gas. The work shows that the radiation can be in equilibrium with the photon condensate without phase boundary. According to this concept the condensate can be considered as an intermediate state when the matter (the substance) experiences physical and chemical action under absorption and emission of the photons.

The radiation is in thermal equilibrium with the substance and the substance experiences the pressure of the radiation because the photons have an impulse. The chemical potentials of the photonic gas and the condensate may be different. The idea of non-zero value of the chemical potential of thermal radiation was already discussed in the literature [1-4]. In this report the characteristic functions of the number of photons U(V, N) and H(p, N) which are necessary for calculation of the chemical potential were found. The temperature dependence of the chemical potential of thermal radiation u=3.602 kT is derived by the differentiation of these functions. One may hope that the characteristic functions of the number of photons and the chemical potential of thermal radiation will allow revealing unknown aspects of chemical, biochemical and electrical actions of thermal radiation in a wide range of temperatures.

Thermal radiation is treated as homogeneous phase equilibrium with a special feature: the pressure of the photonic gas is positive and the pressure of the photonic condensate is negative. From this point of view such medium is neither mixture nor usual solution. This statement is to be based on the theoretical investigation of the conditions of equilibrium and stability of the medium with sign-alternative pressure is carried out under using the thermodynamic laws and the Gibbs' equilibrium criterion. The sun radiation and its condensate are claimers on the medium with alternating-sign pressure.

The thermodynamic scale of efficiency $\zeta(T)$ of the chemical action of solar radiation presented in this work is a necessary tool for choice of optimal design of the solar engines-reactors. It is simple for application while its values are calculated from the data of chemical potentials and temperature obtained experimentally. Varying the values of chemical potentials and temperature makes it possible to model the properties of the working body, its thermodynamic state and optimal conditions for chemical changes in solar engines and reactors in order to bring commercial advantages of alternative energy sources with help of expressions [5]

$\zeta(T) = \eta C / \eta 0 = (uP - uR) / uS /(1-Tm / TS)$,

$\Delta GT = (uP - uR) + (um - uS)$.

- The cell is considered in biology as a biochemical engine. Chemistry and physics know attempts to present the plant photosynthesis as a working cycle of a solar heat engine [6]. The physical action of solar radiation on the matter of nonliving systems during antenna and working cycles of the heat engine is described in [7,8]. In this article the Carnot theorem has been used for calculation of the thermodynamic efficiency of the photosynthesis in plants; it is found that the efficiency is 71%. Earlier the limiting efficiency of green plant was defined to be 5% as a ratio of the absorbed solar energy and energy of photosynthesis products [9, 10].

- Technologies for producing electric contacts on the illuminated side of solar cells are based on chemical processes. Silver technologies are widely used for manufacturing crystalline silicon solar cells. The role of small particles in solar cells was described previously. The introduction of nanoparticles into pores of photon absorbers increases their efficiency. Copper microclusters were chemically introduced into pores of a silver contact. They changed the electrical properties of the contact: dark current, which is unknown for metals, was detected [11].

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8832-20, Session 5

The two-body photon

Randy T. Dorn, Independent Researcher (United Arab Emirates)

The physical observations that light exerts pressure on objects and light is bent by gravity can be considered as evidence that photons do indeed have mass. The theoretical requirement for mass to be convertible to radiant energy which is net electrically neutral yet has alternating positive and negative potentials and an alternating magnetic field leads to the proposal that a photon is simply an electron and positron in a two body orbital union traveling through space. In this paper a simple mechanical model of a photon is presented. It comes directly from conservation of matter and observations of electron-positron annihilation and electron-positron pair production. If electrons and positrons are considered fundamental particles, there is no reason to believe that they change character between annihilation and pair production. Most interpretations of the mathematics of special relativity would lead one to believe that mass cannot travel at the speed of light because the mass or momentum would be infinite at that velocity. However, under the influence of an inverse square force, speed of light particles are actually predicted using accepted mathematical models. Furthermore, the equations of motion of charged particle interactions can be rearranged and interpreted so that the force varies with velocity instead of the mass. This change in perspective makes the concept of speed of light particles entirely plausible and allows a renewed appreciation for the concepts and definitions of classical mechanics.

8832-21, Session 5

Further investigation of an integrated picture of photon diffraction described by virtual particle momentum exchange

Michael J. Mobley, Arizona State Univ. (United States) and Grand Canyon Univ. (United States)

An alternative picture for photon diffraction had been proposed describing diffraction by a distribution of photon paths determined through a Fourier analysis of a scattering lattice where the momentum exchange probabilities are defined at the location of scattering, not the point of detection. This contrasts with the picture from classical optical wave theory that describes diffraction in terms of the Huygens-Fresnel principle and sums the phased contributions of electromagnetic waves to determine probabilities at the point of detection. This revised picture, termed "Momentum Exchange Theory," can be derived through a momentum representation of the diffraction formulas of optical wave theory, replacing the concept of Huygens wavelets with photon scattering through momentum exchange with the lattice. Starting with the Rayleigh-Sommerfeld and Fresnel-Kirchoff formulas and looking at several model experiments, this paper demonstrates that diffraction results from positive and negative photon dispersions through virtual particle exchange probabilities that depend on the lattice geometry and are constrained by the Heisenberg uncertainty principle. The positive and negative increments of momentum exchange exhibit harmonic probability distributions characteristic of a "random walk," dependent on the distance of momentum exchange. The analysis produces a simplified prediction for the observed intensity profile for a collimated laser beam diffracted by a long, straight edge that lends conceptual support for this alternative picture.

8832-22, Session 5

The photonic soliton

Andrew Meulenberg Jr., Univ. Sains Malaysia (Malaysia) and Hi Pi Consulting (United States)

The size stability of the photon has been a puzzle for many decades. However, the self-focusing of a laser beam in matter may provide some guidance to this problem. A conceptual basis for this effect will be accompanied by calculations based on the laser models. It does not necessarily fit. Nevertheless, it leads to better models. The notion of a self-generated light pipe for a photon supports the image of the photon as a soliton. Two photon models are developed. In one, there is a circulating high-energy density that creates a finite-radius light pipe, which thus confines the photon to a core, but with an extended evanescent wave about it. It confines by total internal reflection. In the other, the confinement mode is that of a self-generated graded refractive index (GRIN) optical lens, which does not produce an evanescent wave; but, the electromagnetic energy is spread into the region that would be occupied by the evanescent wave of the first model. The models may be equivalent; both indicate the nature of a relativistic boundary condition that should be imposed on Maxwell's equations to allow inclusion of photons into his model.

8832-23, Session 5

The photon concept revisited

Dmitri V. Voronine, Texas A&M Univ. (United States) and Baylor Univ. (United States); Marlan O. Scully, Texas A&M Univ. (United States) and Baylor Univ. (United States) and Princeton Univ. (United States)

The concept of one photon wave function has attracted interest for decades. People often ask if there exists a 'wave function for the photon' which can be used to understand the nature of the light. Wave function of the classical electrical field and quantum state of the matter system is described in a semiclassical theory. Therefore, many aspects of the photon can be understood with a classical electromagnetic field and the fluctuations associated with vacuum [1]. However, a complete description of radiation-matter interactions is provided by the quantum theory of radiation. To understand the photon concept deeply, we should quantize the radiation field such as E(+)(r,t) = [sigma]k[epsilon]kake-ivktUk(r) where ak are quantum field operators. Thus wave function for a single photon can be defined as [psi][epsilon](r,t) = <0|E(+)(r,t)|[psi]y>. Details are revisited here from Scully and Zubairy's quantum optics book [2] and further discussions are included.

[1] M.O. Scully and M. Sargent III, Physics Today, 25, 38 (1972).

[2] M.O. Scully and M.S. Zubairy, Quantum Optics (Cambridge University Press, Cambridge, 1997).

8832-24, Session 5

The problematic "photon" *(Invited Paper)*

Arnt Inge Vistnes, Univ. I Oslo (Norway)

The concept of a "photon", as an indivisible particle of light, goes back as early as 1905, and the word "photon" was used already in 1926. The concept was not readily accepted. Even today there is no clear consensus on a proper representation of a photon, as the available theoretical formalisms provide little help due to the various interpretational problems that plague them.

The purpose of this talk is to give an overview of the various representations and interpretations that can be associated with the concept of the photon, and to highlight the phenomena that favor more specifically certain interpretations.

I will point out in particular the essential difference between argumentations that are based on physical mechanisms of interaction between fields and atoms, and those that rely on abstract and non-objective principles such as that of "indistinguishability".

I will discuss the difficulty of associating a photon to electromagnetic waves having large wavelengths, as the concept is then far more problematic than for visible light. I will also emphasize the problems associated with using Fourier decompositions to describe photon "modes", as this formalism is essentially meaningful only for continuous waves, and not for particle-like systems. I will illustrate those limitations by means of a comparison with wavelet transform.

Finally, I will insist on the large diversity of problems that arise when trying to go beyond the "wave-particle-dualism" in attempts to get a better understanding of Nature.

8832-25, Session 6

Subtlety in relativity *(Invited Paper)*

Sanjay M. Wagh, Central India Research Institute (India)

I will describe explanations of 1) Michelson-Morley type experiments, 2) Muon decay puzzle, and 3) Doppler's effect in light.

The explanation of the Michelson-Morley type experiments is based on the emission-wave mechanism. The resolution of the muon decay puzzle is based on Pauli's exclusion principle as applied to a system of interacting muon and electrons surrounding it during its passage in the Earth's atmosphere. The explanation of the Doppler shift in frequency is based on the analysis of proper locations on the light front.

Notably, these explanations do not involve either the time-dilation or the length contraction as in the Special Theory of Relativity. That is to say, these explanations do not use the Lorentz transformations. Nevertheless, they are based on the principle that the speed of light is the same for all the observers, whether accelerated or not.

8832-26, Session 6

Spacetime-based model of EM radiation

John A. Macken, Macken Instruments Inc. (United States)

A spacetime based model of an electric field and EM radiation is described. The model assumes that 4 dimensional spacetime has vacuum fluctuations at all frequencies up to Planck frequency. This implies that vacuum has energy density about 10^120 larger than the observable energy density of the universe. The reason that this vacuum energy is not directly observable is discussed.

Gravitational wave theory is used to give insights into EM radiation. We know that gravitational waves propagate in the medium of spacetime. From gravitational wave equations it is possible to derive the impedance of spacetime (Zs = c^3/G) and a wavelength dependent bulk modulus of spacetime. A proposed new constant of nature is derived that converts electric field strength to a quantifiable distortion of spacetime. One key finding is that this new constant shows that the impedance of free

space (Zo ≈ 377 Ω) converts to 4πZs. Therefore light must be wave propagation in the medium of spacetime because light experiences the same impedance as gravitational waves. The particle-like properties of a photon are examined and found to be the result of photons possessing quantized angular momentum.

An electric field is proposed to be a quantifiable polarization of spacetime. An experiment is suggested to test this prediction. This model also implies that gravitational waves should affect the polarization of circularly polarized light. If this effect exists, then a suggested modification of the LIGO experiment would greatly increase its sensitivity.

8832-27, Session 6

Can highly-relativistic particles explain part of the dark Universe

Karl Otto Greulich, Fritz Lipmann Institute (Germany)

In attempts to explain dark matter, an important componen is often neglected: particles such as ultrafast protons/neutrons which have a relativistic mass larger than the Planck mass and are thus invisible. At a critical speed the mass of a particle exceeds that of the Planck mass. Its Schwarzschild radius then becomes larger than its de Broglie wavelength, i.e the particle becomes invisible. For protons/neutrons this is approx. 10 exp19 times of its mass at rest. With the assumption that particles with a rest mass of only the order of 10 000 Sun masses still have kept, since the big bang, such a high speed, it can be explained that the major part of the Universes mass appears as "dark". It also becomes plausible that even today visible mass is generated from virtually the vacuum, simply by decelerating down such fast particles by collisions with slow matter.

8832-28, Session 6

The electrostatic to gravitational force ratio within the Electro-Gravi-Magnetic (EGM) construct *(Invited Paper)*

Riccardo C. Storti, Delta Group Engineering, P/L (Australia)

The Electro-Gravi-Magnetic (EGM) construct is a derived methodology based upon the Polarizable Vacuum (PV) model of gravity and Buckingham Pi Theory (BPT). Their union has produced impressive experimentally verified results consistent with the Standard Models of Particle-Physics and Cosmology. The body of research in this paper is based on the fundamental EGM prediction that Photons are quantized massive propagating units of matter such that, when standard engineering scaling and similarity techniques are applied, the "Many Orders of Magnitude" problem between ElectroStatic and Gravitational Forces is reconciled as a function of Cosmological Expansion.

8832-29, Session 6

Resonant energy absorption and the CTF hypothesis

Michael Ambroselli, Chandrasekhar Roychoudhuri, Univ. of Connecticut (United States)

Antennas in resonant circuits can present an effective aperture (antenna area) much larger than its physical dimensions, in order to absorb energy from the electromagnetic field. Similarly, atoms can absorb energy from fields with energy densities so low that the atom must have an effective diameter on the order of tens of microns. It appears that resonant energy absorption exhibits a sort of 'suction' effect, which causes field energy to converge from a larger into a smaller region. We will discuss how this provides further evidence for the utility of our proposition of a universal, complex tension field (CTF), which can support a multitude of gradients, including the electromagnetic field.

8832-63, Session 6

The influence of gravitation on electromagnetism

Guido Zbiral, Consultant (Austria)

Although photons can be extremely energetic and each form of energy is inseparably associated with gravitation, the Theory of Special Relativity nevertheless assumes that the gravitation of photons - always supposed to be static in nature - is vanishingly negligible. For this reason the photon's gravitation is completely ignored in that theory. This paper, however, casts doubt on the correctness of this assumption and will examine the actual role played by gravitation in electromagnetism.

In the course of this paper, an analysis will lead to the new insight that the gravitation of a photon is as dynamic as the photon itself, but static gravitation does not exist for photons. The dynamic gravitation of a photon appears as gravitational radiation locally bound to the photon and is in close interaction with the photon's electromagnetic radiation. Dynamic gravitation represents the hitherto unknown physical quantity acting in an opposite manner to electrodynamics, thus closing an evident gap in physics.

Furthermore, it will be shown that dynamic gravitation determines the physical properties of photons, such as the speed of light, and must therefore be taken into account with all associated physical considerations. The dynamic gravitation of photons is produced by gravitational quanta, and thus appears in quantised form. Consequently there must exist exactly the same number of gravitational quanta as there are of photons themselves. It is therefore necessary to rethink the physics of photons.

8832-30, Session 7

Epistemological considerations on the foundations of physics *(Invited Paper)*

Ted Silverman, IIAS (United States)

The conceptual foundations of physics are compromised by profound logical difficulties, too many of which have been romantically attributed to the mysteries of a universe "stranger than we can imagine." While foundational problems have always existed in physics the extent to which they currently impede research is well beyond a tolerable limit. Efforts to push past these problems without directly addressing them have little chance for long term success. A tangle of subtly linked conceptual cords must be carefully dissected before fruitful efforts toward unification can proceed.

8832-31, Session 7

Emergent un-quantum mechanics

John Ralston, The Univ. of Kansas (United States)

There is great interest in ``emergent" dynamical systems and the possibility of quantum mechanics as emergent phenomena. We engage the topic by making a sharp distinction between models of microphysics, and the so-called quantum framework. We find the models have all the information. Given that the framework of quantum theory is mathematically self-consistent we propose it should be viewed as an information management tool not derived from physics nor depending on physics. That encourages practical applications of quantum-style information management to near arbitrary data systems. As part of developing the physics, we show there is no intrinsic distinction between quantum dynamics and classical dynamics in its general form, and there is no observable function for the unit converter known as Planck's constant. The main accomplishment of quantum-style theory is a expanding the notion of probability. A map exists going from macroscopic information as ``data" to quantum probability. The map allows a hidden variable description for quantum states, and broadens the scope of quantum information theory. Probabilities defined for

mutually exclusive objects equal the classical ones, while probabilities of objects in more general equivalence classes yield the quantum values. Quantum probability is a remarkably efficient data processing device; the {it Principle of Minimum Entropy} explains how it serves to construct order out of chaos.

8832-32, Session 7

Global sustainability and advances in quantum physics

Juliana H. J. Mortenson, General Resonance, LLC (United States)

Models of global sustainability suggest a near term crash of global economies caused by depletion of world energy resources, rapidly declining industrial output, and food shortages. In scenarios which do not end in catastrophic crash, technology is the key factor which allows the world to avoid a significant decline in global economies: technology which reduces the use of energy resources per unit of industrial or food output, decreases pollution, and increases land yield. To avoid collapse and ensure global sustainability, the ratio of energy input to product output ("EI/PO") must be lowered. Based on scientific consensus regarding energy and thermodynamics, such a technology solution is unlikely, if not impossible. It has previously been shown however that the foundations of twentieth century physics were incomplete and new quantum variables and foundational equations have been discovered. Recent work with these variables has radically changed scientific understandings of energy, thermodynamics, and quantum relationships. The complete physics which is emerging provides scientific mechanisms by which the ratio of energy input to product output can be lowered, and has opened the door to previously unexplored concepts in energy dynamics and resonance science. This on-going scientific revolution may provide the technologies required to sustain global economic development, energy production, resource use, pollution remediation, and industrial and food output.

8832-33, Session 7

Quantum Indeterminism: a direct consequence of Fourier ontology *(Invited Paper)*

Jose R. Croca, Univ. de Lisboa (Portugal)

Quantum mechanics is founded on the Complementarity Principle proposed by NielsBohr for the first time at Volta Conference, September 1927. The mathematical expression of this founding principle are Heisenberg indeterminacy relations. By its turn Heisenberg relations, as shown by Bohr, are a simple consequence of Fourier ontology. In this stealthy way nonlocality, both in time and space, are deeply rooted in quantum mechanics.

In such circumstances the only way to recover causality and a fair locality is to substitute Fourier ontology and assume, since the very beginning, that a finite wave may have a well-defined frequency. The use of local wavelet analyses, in particular Morlet wavelets, allows the derivation of a more general set of uncertainty relations that formally contain Heisenberg relations as a particular case.

Since physical theories are validated or invalidated by experiments let them talk! Experiments have shown to the evidence that the limits imposed by Heisenberg relations can be overcome. Indeed, in modern technology, namely the one related with computers and memory devices, is common for the vanguard to refer that they are working beyond Heisenberg limits, or Fourier diffraction limits. Furthermore, other experiments, that shall be discussed, are devised to test the general validity of Heisenberg relations, and consequently Fourier ontology.

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8832-34, Session 7

Viewing the terrestrial and cosmological phenomena through the eyes of photon wave packets

Chandrasekhar Roychoudhuri, Univ. of Connecticut (United States)

How would photon wave-packets describe terrestrial and cosmological phenomena based on their physical experiences? The presentation will be done by a biased, subjectively driven neural network. So the objectivity behind the methodology of thinking will be defined. Our ontological thinking is still an emerging phenomenon and must continue to be refined iteratively through generations. We must anchor our logical thinking and modeling approach to map the physical interaction processes in nature by visualizing these otherwise invisible processes. Emulation of nature allowed processes is behind our successful invention of technologies, which, in turn, is at the core of our successful evolution since the early days of evolution starting with the various single cells. Hence it is critically important for us to incorporate process mapping methodology on to the immensely successful modern methodology of modeling observable data. But why choose photons and not electrons? Various photons, in contrast to particles, (i) can bring accurate information about the original or secondary "parents" as in QM, Astrophysics, and optical sensors; (ii) can deliver information as in optical communication; and (iii) can deliver energy as in laser material processing. Our story will be woven based on their mutual non-interacting properties, in contrast to interacting particles. Distinguishing between the mathematical superposition principle and physical superposition effects, experienced by detectors, is our key logical platform. We demonstrate that a large number of ad hoc hypotheses from Classical-, QM-, Relativity- and Astro-Physics can be safely removed to make physics more causal and understandable through common sense logics.

Non-interaction of EM waves in the linear domain requires new properties for the cosmic vacuum as a physical and stationary Complex Tension Field (CTF), rather than treating it as a pure vacuum. Acceptance of CTF then enforces a cascade of changes in the prevailing physics hypotheses pertaining to Classical, Relativity, QM and Cosmology, while preserving all the measured phenomena, including the constancy of the velocity of light. 3-D space becomes more relevant than the hypothesis of 4-D space. Optical Doppler shift becomes separately dependent upon the source and the sensor velocities; which then requires us to explain

cosmological redshift as distance dependent dissipative frequency loss, rather than due to optical Doppler shift, obviating the hypothesis for an expanding universe. The hypothesis of wave-particle duality becomes unnecessary to explain physical superposition effects, which, in reality, are transformations experienced by detectors under the influence of simultaneous stimulation by multiple entities at the same time. Most of the apparent mystical behaviors behind light-matter interactions become causal and local, making QM a causal. In classical physics propagation of space and time finite causal signal, instead of non-causal Fourier monochromatic wave existing in all space, makes mathematical models for spectrometry, coherence, dispersion, polarization more appealing while using fewer hypotheses than we do now. Thus, non-interaction of waves becomes a powerful "Occam's razor", while making prevailing physics theories, across the board, to conform to common sense and at the same time underscores the direction of new exploration and development. The symbols in a mathematical theory should correspond, as closely as possible, to the physical parameters of entities under study and the mathematical operators must corroborate real physical interactions between them.

8832-35, Session 7

The Mandelbrot set and the fractal nature of light, the Universe, and everything

Lori Gardi, Robarts Research Institute (Canada)

There is always another way to say the same thing that doesn't look at all like the way it was said before." Richard Feynman. In this essay, a novel approach to cosmology is presented that models the Universe as an iterated function system (IFS) analogous to the famous Mandelbrot Set IFS: z=z2+c, where z and c are complex numbers (M). In theoretical physics, wavefunctions are functions of the complex plane that are commonly used to model the dynamics of particles and waves. In the IFS framework presented herein, complex dynamical systems are generated via the iteration process where the act of iteration corresponds to 1) a change in the state of the system and 2) a change to the wavefunction itself. In this manner, M can be thought of as a wavefunction generator. In this framework, all observables, including gravity and time, are thought to be generated by the iteration process. Feynman understood that there are many ways of looking at the Universe that are equivalent in nature but different psychologically. Understanding cosmology in terms of fractals and iterated function systems requires a paradigm shift in the way we approach cosmology. This is an evidence based dissertation and does not contradict the standard model; rather, it attempts to reconstruct it using the principles of the fractal paradigm as outlined in this essay. It is the contention of the author that in order to understand the true nature of light, the Universe and everything, we must first understand the important role that fractal cosmology plays in the study of our complex dynamical Universe.

8832-36, Session 7

Dark side of quantum mechanics: categorification, reinterpretation, and all that in the sheaf framework

Michael G. Zeitlin, Antonina N. Fedorova, Institute of Problems of Mechanical Engineering (Russian Federation)

We present an attempt of reinterpretation of the standard folklore of the elementary Quantum Mechanics, considered as some ground zero approximation for Local Quantum Field Theory.

First of all, we get rid of the structureless geometrical point as a proper model for the real quantum/physical particle like electron or photon. To do that we need to substitute standard (wave) functions describing states in orthodox formulations by more complicated objects to have a chance to encode information about the possible internal structure of quantum objects in our formal mathematical description.

Here we continue our program (started in arXiv:1109.5035, arXiv:1109.5042) of reconsideration of Quantum Mechanics via some categorification in the powerful sheaf framework.

It allows us to introduce hidden structures, like hidden degrees of freedom and hidden symmetries, into the game and, as a result, to have a chance for a more careful description and interpretation of the well-known set of standard phenomena, including, e.g., self-interference/interaction, entanglement, decoherence.

We start with the description of our base categories also proper for more analytical/computation tools described in companion paper.

After that, we introduce various families of sheaves which allow us to describe our version of the Quantum World, where the category of coherent sheaves play the crucial role in the qudit case while quasi-coherent sheaves are proper for the continuous variable case.

It seems that such a framework together with sheaf language allows us to obtain a natural interpretation for the whole set of phenomena, including transition to the (quasi) classical description, e.g., we will consider the wave function collapse/decoherence/measurement as the inductive limits of some families of sheaves.

In addition, we consider bridges to the more tradition quantization procedures like geometrical and deformation ones.

In companion paper, we apply that machinery to an analysis of the hidden multiscale structure of quantum Wigner-Weyl-Moyal dynamics beyond of the gaussian approximation.

8832-37, Session 8

Quantum theory as the most robust description of reproducible experiments *(Invited Paper)*

Hans De Raedt, Univ. of Groningen (Netherlands); Mikhail I. Katsnelson, Radboud Univ. Nijmegen (Netherlands); Kristel F. Michielsen, Forschungszentrum Jülich GmbH (Germany)

It is shown that the basic equations of quantum theory can be obtained from a straightforward application of logical inference to experiments for which there is uncertainty about individual events and for which the observed frequencies of events are robust with respect to small changes in the conditions under which the experiments are carried out.

8832-38, Session 8

Probability and current density of a single photon

Gavriil Shchedrin, Texas A&M Univ. (United States) and Princeton Univ. (United States); Marlan O. Scully, Texas A&M Univ. (United States) and Princeton Univ. (United States) and Baylor Univ. (United States)

We introduce the concept of the probability and current density of a single photon. The wave function of a single photon is represented by the direct product of the three-component electric and magnetic spinors. We show that the Maxwell equations formulated in terms of electric and magnetic spinors of a single photon can be written in terms of the time-dependent Schr odinger equation for a six-component bispinor. This formulation naturally leads to the current and the probability density for a single photon that satisfies the continuity equation.

8832-39, Session 8

The topological basis of the photon

Robert M. Kiehn, Univ. of Houston (United States)

All physical measurements depend upon finite intervals of space and time. There are only two types of finite power set topologies;

(Kolmogorov) T0 topologies with separation axioms, and Not-T0 topologies without separation axioms. Finite T0 topologies have singlet subsets which are distinguishable in the sense of Particles. Finite Not-T0 topologies have singlet subsets which are indistinguishable in the sense of Waves and Ensembles. In this article, focus is placed on the Not-T0 topologies and their association with waves and photons. Numerous examples will be presented.

8832-40, Session 8

Geometro-dynamics of energy of fermions and photons

Viraj P. Fernando, Natural Philosophy Alliance (Canada)

It is the common belief in today's physics that the energy-momentum equation holds only for fast moving fermion particles. However, this equation is found to be is true for all velocities 0< v< c , upon discerning that there is a fundamental trigonometric relationship pc = mc2 tan?, between the two terms on the left hand side of the equation, which also prompts that the right hand side is mc2.sec2?. Once these relationships are deciphered, we find that the second order term v2/c2 which has hitherto been required to be neglected for the validity of classical mechanics for optical phenomena now assumes its true relational expression as sin2?. By means of geometric representation, this approach enables the visualization of all the phenomena involved in a given interaction in their concatenation. In contrast to a fermion, even though a photon moves by its own intrinsic energy, and undergoes a change of state of motion without the direct application of motive energy pc externally, in photon interactions too an algorithm similar to the fermion algorithm is found to be simulated, and energy effluxes and influxes to and from the field are effected as determined by it. The veracity of the above- mentioned algorithms are demonstrated by applying them in combination to the collision of a photon and an electron as in Compton's experiment. In every interaction without exception, a photon undergoes either an emission of a fraction of its energy (energy-defect) to the field or an absorption of a fraction of energy (energy-absorb) from the field.

8832-41, Session 8

Revising your world view of the fundamental constants

John Ralston, The Univ. of Kansas (United States)

The nature of physical units and fundamental constants may seem elementary, but it is not. For a century units and constants have been delegated to international committees unconcerned with the evolution of theoretical physics. The current situation has locked physics into a perspective a century in the past.

It is almost impossible for those in engineering and applied physics to get consistent information that is not conflicted by contradictory and failed theories of the early 20th century.

By critically re-examining the actual structure of the present system in a new light, we find that unit systems and concepts endemic in Newtonian physics impede the understanding and use of quantum theory. Confronting this finds that Planck's constant cannot be observed in quantum theory, and is entirely a construct of human convention. A cascade of seeming paradoxes and contradictions occurs when Planck's constant is eliminated, yet the end result is a simpler and cleaner vision of what quantum mechanics and quantum field theory really involve. By eliminating redundant holdovers the number and nature of fundamental constants is revised: the fine structure constant is determined more than 100 times more accurately.

The nature of "mass" and mass parameters is changed to eliminate mistakes of the era before quantum mechanics, and dispense with all mystical mumbo-jumbo

8832-42, Session 8

A tower of hidden scales: non-Gaussian patterns in quantum mechanics

Antonina N. Fedorova, Michael G. Zeitlin, Institute of Problems of Mechanical Engineering (Russian Federation)

We present an application of our sheaf-based categorification framework considered in the companion paper to analysis of quantum dynamics inside the Wigner-Weyl-Moyal set-up. The key ingredient of our approach is related to a construction of functorial correspondence between two categories: the first one is described by families of quantum states realized as sections of some category of sheaves, allowing to cover the standard set of quantum phenomena while the second one is a proper arena for the investigation of (non-trivial, non-gaussian) solutions of Wigner-like equations in (at least) the minimal possible pseudodifferential set-up according to the ideology of microlocal analysis. To do that we need to consider together with the usual Hilbert space some underlying topological Hilbertian space with some filtration into subspaces, generated by the action of internal hidden symmetry. As a result, we obtain the analytical description of the whole tower of underlying scales together with the possibility to describe the full quantum evolution, taking into account the abundant hidden quantum structure. It seems that the existence of such rich internal structure is an essential part of any quantum phenomenon in contrast with the classical one.

So, we decompose quantum evolution into a full set of multiscales according to orbits constructed by the action of internal hidden symmetry on the properly filtrated underlying Hilbertian space of states.

Numerical modeling demonstrates the appearance of a big zoo of nontrivial patterns which enlarge an orthodox set of standard states like coherent ones, gaussians, etc. and allow us to have an additional chance for a possible reinterpretation and description of standard things like entanglement, decoherence, (von Neumann) measurements together with an attempt to understand the main features, e.g., hidden content, of base Quantum Mechanics.

8832-43, Session 9

What is a particle? A lesson from the photon *(Invited Paper)*

Karl Otto Greulich, Fritz Lipmann Institute (Germany)

In earlier contributions to this conference series (1,2) a photon model was presented where two Planck charges (Q= e/SQRT fine structure constant) oscillate against each other. It could explain, why electromagnetic radiation is transverse, why E=hv, why the spin of the photon is 1,and why it is self propelliing. Now it is shown that a similar model, again based on the Planck charge,explains essential features of the hydrogen atom and predicts the mass of the electron exactly and that of the proton to better than 0,3 %. Most masses of the heavy (beyond the up and down) quarks and the W, Z and Higgs Boson are predicted with accuracies better than 2 %.One of fhe predicted masses at 70 MeV/c2 cannot be ascribed to a known particle. However, its 1-5 fold is the muon, its twofold is the pion. All other particles are integer multiples of this mass-(2,3)

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8832-44, Session 9

The physical origins of the Uncertainty Theorem

Albrecht Giese, Deutsches Elektronen-Synchrotron (Germany)

Elementary particles can be explained by an interpretation of quantum mechanics founded by Louis de Broglie, the discoverer of the wave properties of a particle.

According to this, elementary particles can be described using a predominantly classical model. This model is derived from the presence of relativity in all matter, and furthermore from properties such as mass, spin, and magnetic moment. According to this model an elementary particle is made up of a pair of sub-particles which orbit each other. The internal field which binds the sub-particles extends outward from the particle. It causes the particle to appear from the outside like a wave, and to undergo interference, for example when passing through a double slit. This understanding conforms to the approach of Louis de Broglie, who characterized the external part of the alternating field as a “pilot wave”.

The problem with measuring the dynamic parameters of an elementary particle is that those parameters are determined by the reaction of its surrounding wave. This surrounding wave on the one hand extends outward from the particle, but on the other hand it is locally concentrated around the position of the particle. This fact, the spatial delimitation, limits the determination of the wave parameters using the rules of the Fourier transform. Hence it reduces the information that can be obtained about the parameters to a degree described by the uncertainty of the measurement of the wave. The properties of the particle itself, however, are not at all uncertain in this view.

This derivation of uncertainty does not support the very general consequences drawn from the uncertainty principle as used by contemporary QM.

To apply this understanding to the photon, we have to assume that the photon has a kind of core, like leptons and quarks. This gives rise to further questions which need to be discussed.

8832-45, Session 9

On the possibility of laser-assisted production and detection of low-energy neutrino beams

Jeff W. Eerkens, Prodev Consultants (United States)

Experiments are discussed to prove or disprove the production and detection of collimated beams of low-energy (eV - keV) neutrinos with the assistance of lasers. Results of quantum-mechanical calculations are given of the relative probability that recoiling counter-propagating neutrino-antineutrino pairs are created instead of laser photons in stimulated emission events, under full obedience of energy, momentum, and spin conservation. This effect generates coherent monochromatic neutrino beams that overlap the internal standing-wave photon beam during stimulated de-excitations of lasing excited states. For a neodymium laser the probability is approximately 10-7. To detect such beams of monochromatic neutrinos and antineutrinos without requiring (anti)neutrino absorptions, one exploits (anti)neutrino-stimulated de-excitations of lasing levels in a second laser aligned with the first one. Excess emitted photons in the second laser induced by resonant (anti) neutrino fly-throughs can be measured by a laser power meter. By preventing photons from the first laser to enter the second one (e.g. by interposing a brick), one can discriminate and observe the effects of resonant fly-through neutrinos crossing the second laser. (Anti)neutrinos pass through nearly all matter (except for MeV (anti)neutrinos that strike nuclei). They can not be absorbed because they possess spin s = 1/2 and excitations/de-excitations in molecules require)s = Vn where n is an integer. This allows them to pass through the earth unimpeded. While absorptions are impossible, they can stimulate de-excitations of excited states without being absorbed if their undulation frequency is resonant with a lasing transition.

8832-46, Session 9

Inadequacies in De Broglie’s theory: rectifications, verifications, and applications

Ravindra K. Sinha, Himanshu Chauhan, Delhi Technological Univ. (India)

The genuine inadequacies persisting in De Broglie’s theory is presented in this paper. De Broglie’s proposed frequency (hν=ymc2) and phase velocity (c2/ν) expressions for matter wave are primarily shown to be inconsistent; and emerged out because of a major inadequate concept of similarity between photon and matter-body. He treated body and photon to be analogous which is inconsistent; in view of the ‘matterlessness’ of photon. The rectifications in the concepts are presented by treating the corpuscle of matter wave as a separate entity, though associated with the body, in a moving mass system. This corpuscle is shown to be actually analogous to photon instead of body itself.

The concept thus provides modified frequency ((hν=(y-1)mc2) and phase velocity expression for matter waves.

The proposed frequency and phase velocity expressions are verified by deriving it from the experimentally verified wavelength and conceptually adequate group velocity (νg=ν) expression. By the integration of thus obtained equation yields out the proposed modified frequency expression.

It is further shown that the substitution of the proposed modified phase velocity expression in the universal wave equation can yield the time dependent Schrödinger’s equation; however, de Broglie’s expression cannot. This shows the appropriateness of the proposed modified phase velocity expression.

Through the proposed modifications a Novel General Quantum Mechanical Wave Equation is derived out, and it is shown that the above proposed wave equation can yield out both Schrödinger’s and Dirac’s Equation Precisely.

8832-47, Session 10

Higgs Boson: God particle or divine comedy? *(Invited Paper)*

Chary Rangacharyulu, Univ. of Saskatchewan (Canada)

While particle physicists around the world rejoice the announcement of discovery of Higgs particle as a momentous event, it is also an opportune moment to assess the physicists’ conception of nature. Particle theorists, in their ingenious efforts to unravel mysteries of the physical universe at a very fundamental level, resort to macroscopic many body theoretical methods of solid state physicists. Their efforts render the universe a superconductor of correlated quasi-particle pairs. Experimentalists, devoted to ascertain the elementary constituents and symmetries, depend heavily on numerical simulations based on those models and conform to theoretical slang in planning and interpretation of measurements . It is to the extent that the boundaries between theory/ modeling and experiment are blurred. Is it possible that they meandering in Dante’s Inferno?

8832-48, Session 10

Geometrical and quantum mechanical aspects in observers’ mathematics

Boris Khots, Compressor Controls Corp. (United States); Dmitriy Khots, Consultant (United States)

When we create mathematical models for Quantum Mechanics we assume that the mathematical apparatus used in modeling, at least the simplest mathematical apparatus, is infallible. In particular, this relates to the use of “infinitely small” and “infinitely large” quantities in arithmetic and the use of Newton – Cauchy definitions of a limit and derivative in

analysis. We believe that is where the main problem lies in contemporary study of nature. We have introduced a new concept of Observer's Mathematics (see www.mathrelativity.com). Observer's Mathematics creates new arithmetic, algebra, geometry, topology, analysis and logic which do not contain the concept of continuum, but locally coincide with the standard fields.

We prove that Euclidean Geometry works in sufficiently small neighborhood of the given line, but when we enlarge the neighborhood, non-Euclidean Geometry takes over. We prove that the physical speed is a random variable, cannot exceed some constant, and this constant doesn't depend on an inertial coordinate system. Certain results and communications pertaining to these theorems are provided

We proved the following theorems:

Theorem A (Lagrangian). Let L be a Lagrange function of free material point with mass m and speed v. Then the probability P of L = mv2/2 is less than 1: P (L = mv2/2) < 1.

Theorem B (Nadezhda effect). On the plane (x, y) on every line y = k x there is a point (x0, y0) with no existing Euclidean distance between origin (0, 0) and this point.

Conjecture (Black hole). Our space-time nature is a black hole: light can't go out far from origin.

8832-49, Session 10

Can one distinguish between Doppler shifts due to source-only and detector-only velocities?

Chandrasekhar Roychoudhuri, Michael Ambroselli, Univ. of Connecticut (United States)

The Ne-atoms in a He-Ne discharge tube and light emitting atoms in different galaxies are QM law-abiding entities. Atoms participating in spontaneous and stimulated emissions must release and perceive photon wave packets as having the same QM-allowed frequency , even when they are statistically executing Maxwellian velocity distribution. Thus, a spontaneously emitted energy packet from a moving Ne-atom will evolve in the CTF as a photon wave packet carrying a true Doppler shifted frequency . But an excited Ne-atom would be able to respond to this Doppler shifted frequency as only if it is executing the same vectorial velocity as the original emitter of this wave packet. It has to nullify the physical Doppler shift of the wave packet by traveling in the same direction with the same velocity. In other words, the 'successful detector' Ne-atom 'to be stimulated' executes a dipolar stimulation at an apparent frequency , such that . All other excited Ne-atoms ignore this stimulating wave frequency as they are non-resonant and are not as prescribed by QM for successful stimulated emission. This is at the root of "inhomogeneously broadened" Ne-gain medium, which gives rise to multiple longitudinal modes in He-Ne lasers. Thus, optical Doppler shift is a function of both the velocities of source and the detector, instead of the relative velocity alone, as in standard classical Doppler shift formulation. We do not use Relativistic Doppler shift formulation, as we find that it cannot model the physical processes that the spontaneous and stimulating Ne-atoms carry out during their lasing operations. Thus distance dependent Cosmological Red Shift should not be explained as due to Doppler effect given by only the relative velocity between any pair of galaxies. We propose a distance dependent dissipative effect, implying that the universe could be "stationary". We then present a simple formulation to account for the distant dependent Hubble red shift by accommodating Hubble constant in our equation.

8832-50, Session 10

On reconciling quantum mechanics and local realism

Donald A. Graft, STMicroelectronics (United States)

Acceptance of nonlocal quantum correlations requires us to reject special relativity and/or probability theory. We can retain both by modifying quantum mechanics to change the handling of separated systems, as quantum mechanics stands in conflict with local realism only in its treatment of separated systems. We must not use the joint probability formula for cases of separated measurements; instead we use the marginals (partial traces) together with whatever priors we have from an understanding of the system. Such a program can reconcile quantum mechanics with local realism. An apparent obstacle to this program is the experimental evidence, but we argue that the experiments have been misinterpreted, and that when correctly interpreted they confirm local realism. By way of example, we describe a local realistic account of one important EPRB experiment (Weihs et al) that is claimed to demonstrate nonlocal entanglement. We present a local realistic system (experiment) that can be calibrated into both quantum and classical domains via adjustment of parameters ("hidden variables") of the apparatus. Weihs incorrectly dismisses these parameters as uncritical. The idea of nonlocal entanglement is seen to be an error. The rest of quantum mechanics remains intact, and remains highly valued as a powerful probability calculus for observables. Without the incoherent idea of nonlocal entanglement, we can leverage powerful classical ideas, such as semiclassical radiation theory, stochastic dynamics, classical noncommutativity/contextuality, measurement effects on state, etc., to augment or complement quantum mechanics. The modified quantum mechanics can live in peaceful harmony with the local realist conception, each offering useful paradigms for describing systems.

8832-51, Session 11

Wave-particle dualism unraveled by Young's double slit experiment *(Invited Paper)*

Axel Heuer, Univ. Potsdam (Germany)

Particle and wave like properties of photons can impressively be demonstrated in Young's double slit experiment. Usually measurements behind the slit provide information either about the path of the single photons or interference can be observed. Today the question of "which-slit" versus "interference" in the double-slit configuration is as relevant as it was in the early days of quantum mechanics [1].

For gaining some deeper insight we set up an experiment using a pair of photons generated by SPDC pumped with a higher order mode (TEM10) [2,3]. One of the SPDC photons, the signal photon, was applied for illuminating the double slit and measuring the single photon interference behind it. The other photon, the idler photon, was used in a reference measurement at the position of the slit using a polarizing beam splitter.

First, the signal photons were obtained at the position of the slit as a function of the position of the entangled idler photons in a coincidence measurement. From this coincidence measurement the "which-slit" information is available.

In a second coincidence measurement the far field interference fringes were obtained for signal photons passing through one of the slits, only, selected by the position of the reference detector measuring the entangled idler photons.

The newest results will be presented and discussed. This may provide new insights in the wave – particle dualism and thus inspire the discussion about the nature of photons.

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8832-52, Session 11

This entirely new situation as regards the description of physical phenomena: The EPR experiment and quantum probability *(Invited Paper)*

Arkady Plotnitsky, Purdue Univ. (United States)

In his reply to A. Einstein, B. Podolsky, and N. Rosen's (EPR's) argument concerning the famous thought experiment that they proposed, the EPR experiment, N. Bohr spoke of it as revealing an "entirely new situation as regards the description of physical phenomena," which he attempted to explain in terms of his famous concept of complementarity. (How successful he was in this attempt is still under debate.) This paper will offer an analysis of the EPR experiment and the Bohr-Einstein exchanges concerning it from a perspective that is rarely considered in the discussion of the experiment, as originally conceived by EPR—that of probability. The role of probability, which came into play in the later versions of the experiment (which used discrete variables, rather than continuous ones as in the original version), and related developments, such Bell's theorem and the Kochen-Specker theorem, was obscured in the discussion of the original EPR experiment, including by Einstein and Bohr. This was primarily because this experiment dealt with predictions with probability equal to unity. Nevertheless, as I argue in this paper, probabilistic considerations are crucial in considering the experiment, and they played a key, if implicit, role in Bohr's argument. As is well known, the EPR thought experiment (for continuous variables) could not be performed in a laboratory, because the particular quantum state considered by EPR is not normalizable. However, certain parametric down-conversion experiments with photons statistically approximate the original EPR experiment for continuous variables, and as such, I shall argue, expressly bring into the foreground the probabilistic dimensions of the original EPR thought experiment, as do other paradigmatic quantum experiments, beginning with the double-slit experiment. I shall consider these actual quantum experiments from this perspective. I conclude with a brief discussion of what the problematic of the EPR experiment tells us about the nature of photons as quantum objects.

8832-53, Session 11

Entangled photons and antibunching phenomena revisited on the basis of various models for light

Andreas P. Thörn, Arnt Inge Vistnes, Univ. I Oslo (Norway)

At what level of energy does a classical experiment become quantum mechanical? Where does classical electromagnetic theory apply and where do we have to turn to quantum mechanics? Is there a sharp line between these two theories? And if so: why, and why at this level? Or if not: what are the common features of the formalisms, and what are the differences? With our upcoming experimental work, we hope to be able to gain some insight into these challenging questions.

We plan to study the transition from classical electromagnetic pulses to single photon level pulses in various experimental setups known to reveal non-classical effects (e.g. antibunching experiment, violation of Bell inequalities). Using a pulsed laser and starting out with moderate pulse power (i.e. with a vast number of photons in each pulse), the experiment will undoubtedly be describable with classical electromagnetic theory. However, as we steadily reduce the power, classical theory may cease to be valid, and quantum mechanics may have to be applied to describe pulses that contain only a single photon or less on average. Investigating if and under which conditions this might happen will hopefully shed some light on where the conflict between classical and quantum theories lies.

I will present in detail our planned experiment and our preliminary results.

8832-54, Session 11

Can violations of Bell's inequalities be considered as a final proof of quantum physics?

François F. Hénault, Lab. d'Astrophysique de l'Observatoire de Grenoble (France)

Nowadays, it is commonly admitted that the experimental violation of Bell's inequalities that was successfully demonstrated in the last decades by many experimenters, are indeed the ultimate proof of quantum physics and of its ability to describe the whole microscopic world and beyond. But the historical and scientific story may not be envisioned so clearly: it starts with the original paper of Einstein, Podolsky and Rosen (EPR) aiming at demonstrating that the formalism of quantum theory is incomplete. It then goes through the works of D. Bohm, to finally proceed to the famous John Bell's relationships providing an experimental setup to solve the EPR paradox. In this communication is proposed an alternative reading of this history, showing that modern experiments based on correlations between light polarization significantly deviate from the original spirit of the EPR paper. It is concluded that current experimental violations of Bell's inequalities cannot be considered as an ultimate proof of the completeness of quantum physics models.

8832-55, Session 11

Observation of bosonic coalescence and fermionic anti-coalescence with indistinguishable photons

Guillaume Adenier, Arnt Inge Vistnes, Univ. I Oslo (Norway)

The symmetrization postulate asserts that the state of particular species of particles can only be of one permutation symmetry type: symmetric for bosons and antisymmetric for fermions. We report some experimental results showing that pairs of photons indistinguishable by all degrees of freedom can exhibit not only a bosonic behavior, as expected for photons, but also a surprisingly sharp fermionic behavior under specific conditions.

8832-57, Session 12

Nonclassical effects in two-photon interference experiments: an event-by-event simulation

Kristel F. Michielsen, Fengping Jin, Forschungszentrum Jülich GmbH (Germany); Hans De Raedt, Univ. of Groningen (Netherlands)

It is shown that both the visibility $V = 1/2$ predicted for two-photon interference experiments with two independent sources and the visibility $V = 1$ predicted for two-photon interference experiments with a parametric down-conversion source can be explained in terms of a locally causal, adaptive, corpuscular, classical (non-Hamiltonian) dynamical system. Hence, there is no need to invoke quantum theory to explain the so-called nonclassical effects in the interference of signal and idler photons in parametric down conversion and a revision of the commonly accepted criterion of the nonclassical nature of light is called for.

8832-58, Session 12

Event-by-event simulation of experiments to create entanglement and violate Bell inequalities

Kristel F. Michielsen, Fengping Jin, Forschungszentrum Jülich GmbH (Germany); Hans De Raedt, Univ. of Groningen (Netherlands)

We discuss a discrete-event simulation approach that does not require the knowledge of the solution of a wave equation of the whole system, yet reproduces the statistical distributions of Maxwell's theory and quantum theory by generating detection events one-by-one.

This event-based approach, which gives a unified cause-and-effect description of quantum optics experiments such as single-photon Mach-Zehnder interferometer, Wheeler's delayed choice, photon tunneling, quantum eraser, double-slit, Einstein-Podolsky-Rosen-Bohm and Hanbury Brown-Twiss experiments [1], has recently been extended to neutron interferometry experiments.

We illustrate the approach by application to single-photon Einstein-Podolsky-Rosen-Bohm experiments [2] and single-neutron interferometry experiments that violate a Bell inequality [3].

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8832-59, Session 12

Einstein-Podolsky-Rosen-Bohm laboratory experiments: data analysis and simulation

Hans De Raedt, Univ. of Groningen (Netherlands); Kristel F. Michielsen, Fengping Jin, Forschungszentrum Jülich GmbH (Germany)

It is shown that data produced by state-of-the-art Einstein-Podolsky-Rosen-Bohm (EPRB) experiments does not support the hypothesis that the statistics of this data is described by quantum theory, this in spite of the fact that the data violates Bell inequalities. Furthermore, it is shown that an event-based simulation model, providing a cause-and-effect description of real EPRB experiments at a level of detail which is not covered by quantum theory, reproduces the results of quantum theory of this thought experiment, indicating that there is no fundamental obstacle for laboratory EPRB experiments to produce data which is in concert with the quantum theoretical description.

8832-60, Session 12

A rational explanation of wave-particle duality of light *(Invited Paper)*

Sergey A. Rashkovskiy, A. Ishlinsky Institute for Problems in Mechanics (Russian Federation)

The wave-particle duality is a fundamental property of the nature. At the same time, it is one of the greatest mysteries of modern physics. This gave rise to a whole direction in quantum physics - the interpretation of quantum mechanics. The Wiener experiments demonstrating the wave-particle duality of light are discussed. It is shown that almost all interpretations of quantum mechanics allow explaining the double-slit experiments, but are powerless to explain the Wiener experiments. The reason of the paradox, associated with the wave-particle duality is analyzed. The quantum theory consists of two independent parts: (i) the dynamic equations describing the behavior of a quantum object (for example, the Schrodinger or Maxwell equations), and (ii) the Born's rule, the relation between the wave function and the probability of finding the particle at a given point. It is shown that precisely the Born's rule results in paradox in explaining the wave-particle duality. In order to eliminate this paradox, we propose a new rational interpretation of the wave-particle duality and associated new rule, connecting the corpuscular and wave properties of quantum objects. It is shown that this new rational interpretation of the wave-particle duality allows using the classic images of particle and wave in explaining the quantum mechanical and optical phenomena, does not result in paradox in explaining the double-slit experiments and Wiener experiments, and does not contradict to the modern quantum mechanical concepts. It is shown that the Born's rule follows immediately from proposed new rules as an approximation.

8833-2, Session 1

John Caulfield at POC: from holographic components to small system integration *(Invited Paper)*

Tomasz P. Jannson, Andrew A. Kostrzewskik, Thomas C. Forrester, Ranjit D. Pradhan, Wenjian Wang, Physical Optics Corp. (United States)

With his exceptional scientific expertise, John Caulfield was involved at POC from its inception (1985) to present. This paper reviews his recent involvement at POC (2006-2012) which includes both optical and less known non-optical scientific and engineering areas.

8833-3, Session 1

Evolution of our understanding of the human visual system and its impact on our intelligent instruments *(Invited Paper)*

Marija Strojnik Scholl, Gonzalo Páez, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

Humans succeeded in empowering machines to respond to stimulus with autonomous action, thus creating intelligent action in very specific environments. Semiconductor-incorporating electronic computers proved amenable to the implementation of procedural rules. Upon consultation with the relevant knowledge bases, machines became intelligent arriving autonomously to a decision to take action on the basis of stimulus.

We reflect on productive cross-fertilization between neurological knowledge and machine vision research. We comment on the development of our understanding about their action circuits activated by the photon stimulus, during Prof. John Caulfield productive life (past 50 years).

8833-4, Session 1

Forward and backward propagation in positive and negative index materials *(Invited Paper)*

Joseph W. Goodman, Stanford Univ. (United States)

In positive index materials, it is convenient to represent forward propagation of monochromatic light by a transfer function in spatial frequency space. Backward propagation can be used as a tool to discover what object gave rise to a field some distance away, using an appropriate inverse transfer function, provided interferometry is used to measure that distant complex field. However, detector noise limits the ability to successfully back propagate weak high frequency components and evanescent components. Consider a sequence of a positive index material sandwiched with a negative index material and followed by a positive index material. In the negative index material, forward propagation becomes identical with back propagation in the positive index material, but without the introduction of detector noise in between. Rather, detector noise is introduced when the image is detected in the final positive index medium. Attenuation associated with the negative index material is the limiting factor in this case.

8833-5, Session 1

3D measurement using circular gratings *(Invited Paper)*

Kevin G. Harding, Dan Gray, GE Global Research (United States)

3D measurement using methods of structured light are well known in the industry. Most such systems use some variation of straight lines, either as simple lines or with some form of encoding. This geometry assumes the lines will be projected from one side and viewed from another to generate the profile information. But what about applications where a wide triangulation angle may not be practical, particularly at longer standoff distances. This paper explores the use of circular grating patterns projected from a center point to achieve 3D information. Originally suggested by John Caulfield around 1990, the method had some interesting potential, particularly if combined with alternate means of measurement from traditional triangulation including depth from focus methods. The possible advantages of a central reference point in the projected pattern may offer some different capabilities not as easily attained with a linear grating pattern. This paper will explore the pros and cons of the method and present some examples of possible applications.

8833-6, Session 1

Tunable focalizers: axicons, lenses, and axilenses *(Invited Paper)*

Jorge Ojeda-Castaneda, Sergio Ledesma, Cristina M. Gomez-Sarabia, Univ. de Guanajuato (Mexico)

We explore the use of two angular varying phase masks, which work as a pair, for implementing tunable focalizers. We show that the proposed optical device is useful for implementing controllable, rotationally symmetric phase delays. The novel pair is applied for synthesizing tunable versions of axicons /1/, lenses /2/ and axilenses /3/. Furthermore, we note that the proposed optical device is also useful for generating and controlling several wavefront aberrations /4, 5/.

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8833-7, Session 2

Multi-wavelength heterodyne holography and interferometry *(Invited Paper)*

Toyohiko Yatagai, Utsunomiya Univ. (Japan)

A new high-speed technique in digital holography is proposed, in which a phase-shifting algorithm utilizing the optical heterodyning effect and a high-speed CMOS camera are employed. In many phase-shifting algorithms, the phase distribution of the object is calculated by using a few reference phases with equal phase difference. In our proposed method, the arbitrary shift, including linear continuous and random phase, is introduced. The resultant phase difference between the object and the reference beams by vibrating an optical system can also be regarded as the phase-shifting introduced by optical heterodyning. The

phase distribution of the object is calculated by Fourier transforming the time-depending interference fringe data. If the reference phase shift is equally introduced to all the data points in the interference fringe image, the phase distribution at the peak frequency component in the Fourier spectrum gives the phase distribution of the object. Since a few hundred or more images were required in this method, a monochromatic CMOS camera with a high frame rate was used.

The principle of heterodyning technique is described. Then, the use of two wavelength in heterodyne phase-shifting holography and interferometry using a monochromatic image sensor is presented to perform surface shape measurement of the object. For color imaging and 3-D display, a three wavelength technique in which three color lasers are used at a same time is developed. Finally, a wide band light source is introduced to heterodyne phase-shifting holography. Its applications to wide range surface profiling and color imaging is discussed.

8833-8, Session 2

Autonomous tracking of designated persons in crowded scenes *(Invited Paper)*

Kaveh Heidary, R. Barry Johnson, Alabama A&M Univ. (United States)

This paper develops an algorithm for autonomous tracking of a person (target) within a crowded and temporally dynamic scene using a multispectral imaging system. The camera is stationary, the field of view is static, and the sensor pixel footprint is on the order of one inch. The operator designates the target to be tracked by selecting a single target-pixel in the first image frame, preferably close to the center of mass of the observable portion of the target in that particular frame. Following the initial designation, the algorithm tracks the target in real-time autonomously with minimal latency even when target obscuration occurs. The tracking algorithm is based on a novel temporally adaptive spatial-spectral filter bank used to detect target presence or lack thereof in the field-of-regard of the video frame produced by the multispectral cameras. The theory of the temporally adaptive spatial-spectral filter is based on an extension of our earlier work on the generalized matched filter bank (GMFB).

8833-9, Session 2

Surface multiplasmonics for optical sensing *(Invited Paper)*

Stephen E. Swiontek, Drew P. Pulsifer, Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States)

Surface-plasmon-polariton (SPP) waves are electromagnetic surface waves commonly used for optical sensing of chemical and biochemical analytes in a host of research settings. These SPP waves are guided by the interface of a metal and a dielectric material. The SPP wave is the resultant of interactions of free electrons in the metal and polaritons in the dielectric which form quasiparticles called plasmon-polaritons that propagate along that interface.

Commonly used prism-coupled optical sensors based on SPP-wave phenomenon can only sense one analyte, because only one SPP-wave can be guided along the interface of a metal and a partnering homogeneous dielectric material. It has been theoretically and experimentally demonstrated that multiple SPP-wave modes can be launched at that interface provided the partnering dielectric material is periodically nonhomogeneous normal to the interface. An example is a chiral sculptured thin film (CSTF). If the porous regions of the CSTF are infiltrated with a fluid, the angular locations of the SPP-wave modes shift and the device behaves like an optical sensor.

Therefore, a 30-nm-thick aluminum film was deposited onto an SF-11 glass substrate, followed by a partnering lanthanum-fluoride CSTF which was three- or four-periods thick with a pitch of 400 nm. The sample was then affixed to an SF-11 right-angle prism and the reflected intensities of a p-polarized plane wave at different angles of incidence were recorded. Multiple SPP-wave modes shifted when the void regions of the CSTF were infiltrated with a fluid, thus demonstrating a surface-multiplasmonics sensor.

8833-10, Session 2

Uses of spatial light modulators for colour optical processing *(Invited Paper)*

Juan Campos, Univ. Autònoma de Barcelona (Spain); Ignacio Moreno, Univ. Miguel Hernández de Elche (Spain); Josep Nicolas, CELLS - ALBA (Spain); María J. Yzuel, Univ. Autònoma de Barcelona (Spain)

In this work we review the use of spatial light modulators (SLMs) for optical processing applications involving colour management. These applications include their use in optical correlator architectures to perform correlation based pattern recognition. We include pioneering results in collaboration with H. J. Caulfield where colour information was introduced onto the optical correlator by means of gratings with different orientation, frequency and amplitude. This allowed the application to colored scenes of the techniques of coherent optical correlation. The application of SLMs in this subject allowed the realization of optical processing with real time programmable operations, and the realization of efficient phase-only Fourier transform matched filtering.

Nowadays the use of SLMs to manage colour optical processing extends to applications including colour digital holography, multispectral and hyperspectral filtering and imaging, polarimetric sensing in different spectral bands, or the spectral control required for pulse shaping. Here we analyze techniques for the spectral characterization of liquid crystal SLMs. We analyze the spectral characteristics of the optical modulation properties of liquid crystal SLMs. We also review some of the advances carried out in the last fifteen years in their use for some of the above-mentioned applications.

8833-11, Session 3

Compressive imaging: a new field benefiting of classical optical signal processing techniques *(Invited Paper)*

Adrian Stern, Ben-Gurion Univ. of the Negev (Israel)

In a paper published 15 year ago ["Perspectives in optical computing," Computer , 31(2), 22-25, 1998] Prof. Caulfield shared his perspective on the role of optics in information processing. In a retrospective view on optical computing and optical signal processing, based on his thirty years' experience in the field, he pointed on the misdirected effort towards replacing non-optical computers with all-optical ones. Rather than supplanting computers electronics he suggested that optics can be of great benefit for certain other information processing tasks. Among such tasks he pointed on inherent optical applications and 2D array mapping. Here we show that these tasks can be used for a somehow related field; computational imaging. Particularly, we will refer to compressive imaging, which is a field that seeks to implement the theory of compressive sensing (CS) for optical imaging. Compressive sensing is considered a huge breakthrough in signal acquisition. CS theory offers a mathematical framework which allows us to reconstruct the data from substantially less measurements that imposed by the Shannon-Nyquist theorem. CS theory requires that the signals to be measured have a sparse representation in some mathematical domain, a property that all human-intelligible images have, and using a prescribed sensing mechanism. We show that the required sensing operators can be readily implemented with techniques developed for optical signal processing, such as optical Fourier filters, optical matrix vector multipliers, and anamorphic processors.

8833-12, Session 3

Comparative analysis between two different glitter functions for deducing statistical properties of sea surface slopes *(Invited Paper)*

José Luis Poom-Medina Sr., Univ. de Sonora (Mexico); Josué Álvarez-Borrego, Ctr. de Investigación Científica y de Educación Superior de Ensenada (Mexico); Angel Coronel-Beltran, Univ. de Sonora (Mexico); Beatriz Martín-Atienza, Univ. Autónoma de Baja California (Mexico)

The description and interpretation of ocean waves requires statistical techniques due to the nature of the sea surface considered as a continuous random process. This dynamical system is a stationary stochastic process of Gaussian type as a first approximation. One important feature of sea surface is the mean and the variance of the waves. These parameters can be found when sea waves are studied with pressure sensors, but is so expensive. In this paper a Gaussian glitter function is used as a first approximation to a real glitter function and some statistical properties like means and variances are calculated in order to find a statistical relationships between the glitter pattern of the sea surface and the sea surface slopes. In this work, the analytical solutions found for the mean and variances are different mathematically using Gaussian glitter function instead rect function, but both results are very similar, for instance they are qualitatively identical but quantitatively different as shown in the graphs obtained with our new analytical equations.

We can interpret from the graphics obtained from both functions for modeling the variance of the intensities of the images as a function of the variance slope have the same statistical behavior. In our new graphs we can observe that the variance of the intensities of the images have smaller values than those reported by other authors. These results suggest that when the Gaussian glitter function was used causes smaller values in the frequencies that contain the sea surface wave power spectrum.

8833-14, Session 4

Simultaneous and similar ideas with John Caulfield *(Invited Paper)*

W. Thomas Cathey Jr., Univ. of Colorado at Boulder (United States)

John and I were both interested in holography and ways to obtain the reference wave that is needed to interfere with the wave coming from the object. I was working for Autonetics, in Anaheim, Califonia. The company was more interested in patents than papers, so I filed a patent on an idea that I had for obtaining a mutually coherent reference wave from the object wave. At about the same time, John submitted a paper with almost exactly the same title. The topic that we jointly worked on was related to ways to modulate the wavefront of a coherent wave, using the information from an image formed with incoherent light.

8833-15, Session 4

Hijacking of the 'holographic principle' by cosmologists *(Invited Paper)*

Chandrasekhar Roychoudhuri, Univ. of Connecticut (United States)

The Ne-atoms in a He-Ne discharge tube and light emitting atoms in different galaxies are QM law-abiding entities. Atoms participating in spontaneous and stimulated emissions must release and perceive photon wave packets as having the same QM-allowed frequency , even when they are statistically executing Maxwellian velocity distribution. Thus, a spontaneously emitted energy packet from a moving Ne-atom will evolve as a photon wave packet carrying a Doppler shifted frequency . But an excited Ne-atom would be able to respond to this Doppler shifted frequency as only if it is executing the same vectorial velocity as the original emitter of this wave packet. It has to nullify the physical Doppler shift of the wave packet by traveling in the same direction with same velocity. All other excited Ne-atoms ignore this stimulating wave packet as they perceive the carrier frequency as different shades of , but not as .This is at the root of "inhomogeneously broadened" Ne-gain medium, which gives rise to multiple longitudinal modes in He-Ne lasers. Thus, optical Doppler shift is a function of both the velocities of source and the detector, instead of the relative velocity alone. Thus distance dependent Cosmological Red Shift should not be explained as due to Doppler effect given by only the relative velocity between any pair of galaxies. We propose a distance dependent dissipative effect, implying that the universe could be "stationary".

8833-16, Session 4

Holography: origin, development, and beyond *(Invited Paper)*

Francis T. Yu, The Pennsylvania State Univ. (United States)

I shall discuss the origin of wave front reconstruction, which could have been happen as the development of the Magic Mirror or See-Through Mirror in ancient China. Although the concept of wave front reconstruction was first demonstrated by Dennis Gabor in 1948, but a rather similar image sampling was due to Ives in 1906 for color imaging. Nonetheless there are basically two types of wave front reconstructions that have been developed, namely Leith's transmission-type holography and Dennisyuk's reflection-type holography. However Leith's transmission-type hologram is profoundly related to Ives sampling photography, and Nennisyuk's reflection-type hologram is in fact, as I see it, the legacy of Lippmann's color photography. Nevertheless the successful rediscovery of holography must be due to the development of a strong coherent source, known as the laser. Yet the original purpose for the development of holography was mainly to reproduce a truly three-dimensional imagery, but it has a much deeper application far beyond the legacy, as I shall be shown some of them in this talk.

8833-17, Session 4

A theoretical comparison of Fresnel based digital holography and phase retrieval from the transport of intensity equation. *(Invited Paper)*

Damien P. Kelly, Technische Univ. Ilmenau (Germany); Lysann Megel, Thomas Meinecke, Technische Univ Ilmenau (Germany); Stefan Sinzinger, Technische Univ. Ilmenau (Germany)

Holography is now a widely established imaging and inspection tool, that allows the amplitude and phase of an optical wavefield to be directly measured. It continually finds new applications in metrology and biology. Originally holograms were recorded on photographic plates, which needed to be developed before the hologram could first be inspected. In modern holography, these analog recording media have been replaced, by CCD and CMOS digital arrays. These digital arrays differ in several regards from earlier recording media and have an important influence on the properties of the reconstructed holograms. Several of these different properties are explored in this conference paper and contrasted with what would be expected for analog recording media. While measuring the amplitude and phase of an optical wavefield is important, often one wishes to control the optical distribution at a given plane. This can be achieved using diffractive structures that have been designed carefully using iterative Fourier transform based algorithms. Here we review some of our recent work in this area.

8833-18, Session 4

Color sensing under microwaves *(Invited Paper)*

Debesh Choudhury, Neotia Institute of Technology, Management and Science (India)

Color of an object is a perception under the illuminating light source. The wavelength of the illuminating source and the detector 'eye' play vital roles in color perception. Equally important is the color object itself. Inspired by recent results of artificial color due to Caulfield [1], we present a methodology for sensing visual colors under microwaves. We try intuitive experiments using a Gunn diode as the microwave source and a horn antenna to sense the transmitted microwaves through the objects. The objects used are glasses filled with water of different colors. The dielectric constant of water changes due to the different colors. The transmitted microwave power through the objects is detected which is proportional to the color information of the liquid objects. The sensed color signals are enhanced using Caulfield-Maloney normalization [2]. Preliminary results validate the feasibility of discriminating otherwise visual colors under microwave illumination. Caulfield's presumptions worked nicely in simple microwave experiments [3]. This research finding indeed paves down a way for extending artificial color in the microwave bands.

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8833-19, Session 4

Object detection by optical correlator and intelligence: recognition surveillance systems *(Invited Paper)*

Yunlong Sheng, Univ. Laval (Canada)

We report our recent work on robust object detection in high-resolution aerial imagery in urban environment for Intelligence, Surveillance and Recognition (ISR) missions. Our approaches used the simple linear iterative clustering combining regional (color) and edge (space distance) information to form the superpixels. The irregularity in size and shape of the superpixels measured with the Hausdorff distance served to determine the salient regions in the very large-scale aerial images. Then the car detection was performed with the component-based approach. The superpixels were merged statistically to regions, which were described by the radiometric, geometrical moments and shape features, and detected using the Support Vector Machine (SVM). The cast shadow are detected and removed by a radiometry based tricolor attenuation model. Object parts detection is less sensitive to occlusion, rotation, and scale, view angle and illumination changes than detecting the object as whole. The car parts were combined to cars according to unique spatial relations with a deformable object-model. On the other hand, we use the invariant scale invariant feature transform features to describe superpixels as belong to vehicle or non-vehicle classes by the SVM. The classified superpixels are clustered to the detected cars by unsupervised Affine Propagation clustering. From our own experience we trace how the excellent historic ideas by pioneers as H. J. Caulfield in early days for optical pattern recognition, such as the composite matched filters, have been inherited transformed and reinvented in the new approaches to achieve tremendous research progress.

8833-20, Session 4

Energy efficient computing exploiting the properties of light *(Invited Paper)*

Joseph Shamir, Technion-Israel Institute of Technology (Israel)

Energy dissipation in computing stems from fundamental theoretical considerations as well as from the physical nature of electronic processes. A theoretical lower limit of energy dissipation is rooted in the operation of traditional Boolean logic gates that have two inputs and only one output. As a consequence, information is lost on the way and the input cannot be reconstructed from the output. We say that this operation is irreversible and, from entropy considerations, the loss of information is also associated with dissipation of energy. Electronic computers also suffer an additional source of energy dissipation caused by the motion of electrons involved for information transmission and processing. To move electrons electric fields must be applied and energy dissipating currents must be induced.

To achieve a significant reduction in the loss of energy both sources of energy dissipation can be addressed. The lower theoretical limit of energy dissipation can be mitigated by replacing arrays of traditional Boolean logic gates by other methods of implementing logic operations. In particular, a slight modification of the concept of computing allows the incorporation of fundamentally lossless optical processes as part of the computing operation. Moreover, unlike electrons, the propagation of light does not require energy consumption except for the light generation and its final detection. One possible implementation is based on directed logic networks exploiting reversible optical logic gate arrays.

8833-21, Session 4

The amazing evolutionary dynamics of non-linear optical systems with feedback *(Invited Paper)*

Leonid P. Yaroslavsky, Tel Aviv Univ. (Israel)

Optical systems with feedback are, generally, non-linear dynamic systems. As such, they exhibit evolutionary behavior. In the paper we present results of experimental investigation of evolutionary behavior of several models of such systems. The models are modifications of the famous mathematical "Game of Life". The modifications are two-fold: "Game of Life" rules are made stochastic and mutual influence of cells is made spatially non-uniform.

New phenomena in the evolutionary behavior of the models are reported. Among them: Optical systems with feedback are, generally, non-linear dynamic systems. As such, they exhibit evolutionary behavior. In the paper we present results of experimental investigation of evolutionary behavior of several models of such systems. The models are modifications of the famous mathematical "Game of Life". The modifications are two-fold: "Game of Life" rules are made stochastic and mutual influence of cells is made spatially non-uniform.

New phenomena in the evolutionary behavior of the models are reported. Among them: (i) "Ordering of chaos". Formation from seed patterns of stable ordered maze-like patterns with chaotic "dislocations" that resemble natural patterns, which one can frequently find in the nature, such as finger prints, zebra skin, see shell, magnetic domain structure patterns and alike. These patterns and their fragments exhibit remarkable capability of unlimited growth.

(ii) "Self-regulated growth". Growth of "chaotic live" formations into "communities" bounded, depending on the model, by a square or hexagon, until they reach certain critical size, after which the growth stops.

(iii) "Life in a bounded space" and "Coherent shrinkage". After the growth stops, square or hexagon bounded "communities" stabilize in their size for a while remaining active within their bounds and demonstrating a kind of "life in a bounded space", and then, after certain number of iteration steps began shrinkage and finally degenerate into one of stable or oscillating patterns preserving in this process their bounding shape until the very end.

8834-1, Session 1

How Hamilton's memoir to the Royal Irish Academy led to Transformation Theory and nonimaging optics *(Invited Paper)*

Roland Winston, Univ. of California, Merced (United States)

In a memoir on optics presented to the Royal Irish Academy by W. R. Hamilton in 1824, the foundations of transformation optics, nonimaging optics as well as advanced dynamics can be found.

We explore the connections that had remained hidden for over a century.

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8834-2, Session 1

Fast implementation of Oliker's ellipses technology to build free form reflector

Simon Magarill, Synopsys, Inc. (United States)

The field of illumination optics has a number of applications where using freeform reflective surface to create a required light distribution can be beneficial. Oliker's concept of combining elliptical surfaces is one foundation for forming a reflector that can create an arbitrary illuminance distribution. An approach that leads to a fast implementation of this concept is presented and demonstrated. It is based on analytical computation of a 3D cloud of points in order to map the reflector shape that provides the required flux distribution. The flux delivered to chosen zones across the target can be calculated based on its location and on a number of associated cloud points. The method includes the optimization of individual ellipses parameters to achieve the required flux distribution without raytracing through the reflector geometry. Such strictly analytical optimization is much faster than building reflector geometry and performing a raytrace at each step of the optimization. The 3D cloud of points that is generated from the optimization can be used as an input to a standard SolidWorks feature that is then used to build a loft surface. This surface consists of adjacent elliptical facets and would be smoothed as a final step to maintain continuous irradiance across the target. Secondary operation to smooth surface profile between elliptical facets is discussed.

8834-3, Session 1

Mapping algorithm for freeform construction using non-ideal light sources

Chen Li, Dirk Michaelis, Peter Schreiber, Andreas Bräuer, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Using conventional mapping algorithms for the construction of illumination freeforms arbitrary target pattern can be obtained for idealized sources, e.g. collimated light or point sources [1,2,3]. Each freeform surface element generates an image point at the target. For sources with a pronounced extension and ray divergence, e.g. an LED with a small source-freeform-distance, the image points are blurred. These individual light distributions of each freeform element are taken into account in a mapping algorithm [4]. To this end the method of steepest decent including special weighting and smoothing procedures are used to adapt the mapping goal. The corresponding linear optimization matrix is gained by conventional raytracing. Nontrivial source geometries, like LED-irregularities due to bonding or source fine structures, and a complex ray divergence behavior can be easily considered. Additionally, Fresnel losses and even stray light are taken into account.

The algorithm is applied to several design examples. A homogeneous LED-illumination of a tilted or bended target and the generation of a structured target pattern are discussed. Finally, freeform designs for clusters of LED-sources are presented.

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8834-4, Session 1

Design of light concentrators for Cherenkov telescope observatories

François F. Hénault, Pierre-olivier Pettrucci, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); Bruno Khélifi, Laboratoire Leprince-Ringuet, Ecole Polytechnique (France); Jürgen Knödlseder, Institut de Recherche en Astrophysique et Planétologie (France); Michael Punch, Université Paris 7 Denis Diderot (France)

The Cherenkov Telescope Array (CTA) will be the largest cosmic gamma ray detector ever built in the world. It will be installed at two different sites in the North and South hemispheres and should be operational for a minimal period of 30 years. In order to cover the desired energy range, the CTA is composed of typically 50-100 collecting telescopes of various sizes (from 6 to 24-m diameters). Each of them is equipped with a focal plane consisting of 1500 or 2000 Photomultipliers (PM) equipped with light concentrating optics, whose double function is to maximize the amount of energy collected by the telescope, and to block any stray light originating from the terrestrial environment. Two different optical solutions have been designed, respectively based on a CPC (i.e. a Winston Cone concentrator), and on a purely dioptric concentrating lens. In this communication are described the technical specifications, optical designs and performances of the different solutions envisioned for all those light concentrators. The current status of their prototyping activities is also given.

8834-5, Session 1

Intergrating refractive media into nonimaging designs: a self-consistent approach

Lun Jiang, Roland Winston, Univ. of California, Merced (United States)

The concept of skew invariant in nonimaging optics is applied to static symmetry-breaking solar collectors computationally by using genetic algorithm and Monte Carlo ray-tracing to optimize the annual energy yield of the collectors. The simulation result shows that the concentrator can achieve an optimized concentration with rejecting minimum solar radiation, which increases the efficiency and annual yield of the collectors. Furthermore, the results are compared with both the theoretical limit and the experimental data from translational symmetrical compound parabolic solar collectors.

8834-6, Session 1

Angular restriction of photon emission for ultra-efficient photovoltaics

Avi Braun, Eugene A. Katz, Daniel Feuermann, Ben-Gurion Univ. of the Negev (Israel); Brendan M. Kayes, Alta Devices, Inc. (United States); Jeffrey Gordon, Ben-Gurion Univ. of the Negev (Israel)

We present experimental evidence of enhancing the performance of ultra-efficient solar cells by external recycling of photon emission – based on the strategy of increasing open-circuit voltage by reducing radiative recombination. It is equivalent to restricting the angular range of photon emission, and can only be effective in solar cells with high external luminescent efficiency. This has precluded the enhancement from being observable in today's photovoltaic technologies. However, it is attainable with the latest generation of champion single-junction one-sun thin-film GaAs cells. The measurements are understandable in terms of basic photovoltaic thermodynamics.

8834-7, Session 2

The intersection of photonics and nonimaging optics in luminescent solar concentration *(Invited Paper)*

Noel C. Giebink, The Pennsylvania State Univ. (United States)

Optical concentration is a powerful and near-term strategy to lower the cost of electricity produced from established solar cell technologies because it reduces the cell area needed to generate a given amount of power. Whereas passive geometric optical concentrators are invariably bound by the sine limit, luminescent solar concentrators (LSCs) can in principle achieve high concentration ratio (>100x) without tracking the Sun. These devices traditionally consist of a transparent slab embedded with a chromophore that absorbs sunlight and actively re-emits it back into the slab, where it is trapped by total internal reflection and absorbed by photovoltaic cells attached to the edges. Despite their promise, however, practical LSCs have reached only a fraction of their theoretical potential, limiting their utility to date.

We are exploring a new opportunity to improve LSC performance by photonically controlling their spontaneous emission pattern and leveraging the increased directionality together with nonimaging optics to boost output intensity. Here, we discuss initial results based on the use of a simple thin-film bilayer that produces sharply directed conical emission and show that incorporating it on macroscopic freeform waveguides results in optical pseudo-potentials that act like in-plane graded index variations, channeling the flow of light and creating high intensity 'hot spots' at particular locations within the LSC. These results point toward an opportunity to design a new class of 'distributed' nonimaging waveguide surfaces that operate over the course of many bounces to optimally transform low etendúe luminescence for maximum geometric concentration.

8834-8, Session 2

Modeling light propagation in semiconductor-based luminescent solar concentrators

Derya Sahin, Boaz Ilan, Univ. of California, Merced (United States)

This research is focused on modeling light propagation in luminescent solar concentrators. We show the techniques that can be practical to use in the applications in the research areas of involving radiation and transport problems, specifically in solar science. We use two different approaches: radiative transport theory and Monte Carlo simulations for designing effective luminescent solar concentrators (LSCs). Our main goal is to inform the synthesis efforts of the optimal design parameters and obtain the results which can be used to develop LSCs based on semiconductor anisotropic nanorods.

Monte-Carlo (MC) simulations for photon transport have been commonly used tool to compute the performance metrics of LSCs. The optimal design parameters such as the optimal particle concentration, the optimal LSC size can be found by MC simulations. However, the convergence rate of MC simulations is slow. The overall computational time depends on the number of photons and the area of the reabsorption cross-section of the particles' spectra. Therefore, we seek to find an alternative method to model the light propagation in LSCs We study physical, analytical and computational modeling of the absorption and luminescence of light within the framework of radiative transport theory. This study highlights the role of radiative transport theory in modeling light propagation in luminescent media such as LSCs.

8834-9, Session 3

New Fresnel-Köhler optical design: 9-fold photovoltaics concentrator

João Mendes-Lopes, Univ. Politécnica de Madrid (Spain); Pablo Benítez, Light Prescriptions Innovators, LLC (United States); Pablo Zamora, Univ. Politécnica de Madrid (Spain); Juan C. Miñano, Light Prescriptions Innovators, LLC (United States)

Non-uniform irradiance patterns created by Concentrated Photovoltaics (CPV) systems over Multi-Junction Cells (MJC) can originate significant power losses. Furthermore, when chromatic aberrations between irradiance distributions over the different MJC sub-cells are significant, power losses increase considerably, especially when considering 4, 5 and 6 junction cells.

Recent advances in optical designs for CPV, namely Fresnel-Köhler (FK) technology, proven that a spectral balanced high irradiance uniformity is achievable for systems of 850-1000x and large acceptance angle. However, when aiming for larger concentrations, irradiance uniformity decreases for the same optical design family.

Interest on Silicon-on-Glass (SoG) lens has been growing due to the combination of mass production simplicity (injection molding) and high resistance to external factors. SoG lens refractive index is affected by thermal changes, affecting considerably spectral balance of irradiance distributions.

A new CPV optical design, with large acceptance angle and prepared to overcome these effects, is presented.

The 9-fold Fresnel-Köhler (FK-9) 1000x concentrator, with acceptance curve of 1.19º, is based on a SoG nine sectors Fresnel lens combined with a Secondary Optical Element with nine refractive free-form surfaces.

The advanced design was developed such that the performance features (concentration-acceptance products - CAP- between 0.62-0.66, depending on design parameters, excellent irradiance uniformity and spectral distribution) are kept when concentration increases to 2000x and when SoG lens refractive index is affected by thermal effects, revealing excellent tolerance to manufacturing and external factors.

This paper will show the main design features, along with realistic performance simulations considering all spectral characteristics of the elements involved.

8834-10, Session 3

FK concentrator outdoor measurements

Maikel Hernández, Juan F. Vilaplana, Light Prescriptions Innovators Europe, S. L. (Spain); Pablo Benítez, Univ. Politécnica de Madrid (Spain); Rubén Mohedano Arroyo, Light Prescriptions Innovators Europe, S. L. (Spain); Pablo Zamora, Juan C. Miñano, Univ. Politécnica de Madrid (Spain)

The FK is a two-stage optical concentrator for CPV, composed by a

Fresnel lens working as POE and a refractive element working as SOE. Both elements are divided into four sectors in order to perform Köhler integration, for uniform irradiance purposes. The FK concentrator has demonstrated that compares very well with other Fresnel-based concentrator optics, thanks to: (1) high optical efficiency; (2) large tolerance to tracking misalignment and manufacturing errors, thanks to a high CAP; (3) good irradiance uniformity and low chromatic dispersion on the cell surface.

In general, CPV optical concentrators provide non-ideal irradiance profile on the cell surface, presenting certain degree of non-uniformity and chromatic dispersion. Irradiances with uneven profiles and high chromatic dispersion lead to losses in fill-factor and module electrical efficiency. Additionally, when the module presents manufacturing or tracking misalignment, these negative effects are magnified entailing even larger module efficiency losses. The FK, a concentrator providing an even irradiance and low chromatic dispersion profile ensures high module electrical efficiency.

Recent on-sun measurements carried out on an FK mono-module prototype have already shown outstanding results, achieving electrical efficiencies over 34% (no AR coating applied on SOE) for the SoG case. Since in this case a first prototype of this design has been used, optical elements are not perfectly optimized yet. This fact brings enough room to predictably go over efficiency values of 35% (additionally applying an AR coating on the SOE) during the next months.

8834-11, Session 3

Optofluidic approaches to stationary tracking optical concentrator systems

Marco Stefancich, Adam Silvernail, Carlo Maragliano, Matteo Chiesa, Samuele Lilliu, Marcus Dahlem, Masdar Institute of Science & Technology (United Arab Emirates)

Etandue conservation limits static concentrators with high angular acceptance to low concentrations ratios [1]. Large light rejection angles are, however, an important limiting factor system efficiency [2], in flat panels and photovoltaic concentrator systems (CPV). Mechanical tracking allows the use of low acceptance systems by maintaining the system optical axis aligned with the sun direction. This raises, however, reliability issues [3] and prevents CPV from integration in urban and residential environments. Attempts to integrate the tracking in the panel have been made [4] but, besides some notable recent pioneering work [5], mechanical systems are still being used.

We propose to achieve a stationary tracking (non imaging) optical concentrator (STOC) by modifications of the system optics based on the manipulation of liquid interfaces or multiphase systems.

Optofluidic allows to dynamically modify the focal length of a liquid lens [6], the direction of a beam by electrowetting prisms [7] or the state of an optical switch [8]. A transition between reflective and transparent state can be associated to first order phase transition in multiphase systems. Each of these effects provides a possible approach to STOC.

We demonstrate, in a suitable multiphase system, a thermally induced transition between opaque and transparent state being used, together with a micro-optic lens system and a planar slab waveguide, in a novel concept of STOC.

The same results will be demonstrated by an electrophoresis based free space optical router, coupled with stationary lens and slab waveguide.

Theoretical framework, multiphysics modeling and preliminary experimental results will be discussed.

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8834-12, Session 3

Wet-chemistry based selective coatings for concentrating solar power

Daniel Feuermann, Ben-Gurion Univ. of the Negev (Israel); Avi Kribus, Eran Maimon, Yuri Flitsanov, Tel Aviv Univ. (Israel); Oleg Skolnik, Ben-Gurion Univ. of the Negev (Israel); Camille Zwicker, Liraz Larush, Daniel Mandler, Shlomo Magdassi, The Hebrew Univ. of Jerusalem (Israel)

Spectrally selective coatings are common in low and medium temperature solar applications from solar water heating collectors to parabolic trough absorber tubes. They are also an essential element for high efficiency in higher temperature Concentrating Solar Power (CSP) systems. Selective coatings for CSP are usually prepared using advanced expensive methods such as sputtering and vapor deposition. In this work, coatings were prepared using low-cost sol-gel methods. Solutions of alumina/silica sol gel were prepared and then dispersed with black spinel pigments. The black dispersions were applied by spray/roll coating methods on stainless steel plates. The spectral emissivity of sample coatings was measured in the temperature range between room temperature and 500°C. Emissivity at wavelengths of 400–1700 nm was evaluated indirectly using multiple measurements of directional reflectivity. Emissivity at wavelengths 2,000–14,000 nm was measured directly using a broadband IR camera that acquires the radiation emitted from the sample, and a range of spectral filters. The longwave measurements were done at temperatures above 200°C in order to obtain sufficient emitted radiation signal. Emissivity measurement results for a range of coated samples will be presented, and the impact of coating thickness, pigment loading, and surface preparation will be discussed.

8834-13, Session 3

Spectrum-splitting module for illumination and photovoltaic operation using faceted daylighting structure

Shelby D. Vorndran, The Univ. of Arizona (United States); Michael Gordon, College of Optical Sciences, The Univ. of Arizona (United States); Juan M. Russo, Deming Zhang, Raymond K. Kostuk, Yuechen Wu, The Univ. of Arizona (United States)

A spectrum-splitting photovoltaic module using slanted reflection holograms is proposed. The module is intended for a 1-axis tracking rooftop installation. In addition to photovoltaic (PV) electricity generation, a portion of the spectrum is directed onto a secondary target for greenhouse illumination or interior daylighting. The module consists of alternating strips of PV cells and illumination regions. A reflection hologram with varying slant angle placed directly above the PV cell splits the spectrum by diffracting a spectral band at an angle greater than the critical angle of the substrate. This light makes one total internal reflection (TIR) before reaching an illumination region. To distribute the diffracted light into the building, a custom-shaped daylighting structure is matched to the incoming light's angular range, allowing escape from TIR and entrance into the building. The hologram and illumination structure are designed for maximum irradiance uniformity and spectral uniformity.

Raytracing software will be used to model the distribution of spectral irradiance upon the PV cell area and building interior. The system will also be modeled under various atmospheric conditions from direct to diffuse. Several ratios of PV to illumination area are evaluated, and tracking tolerance of the system is discussed. Losses in the module will be addressed, and the final design will be optimized for maximum optical efficiency.

8834-14, Session 4

Gradient-index lens design with quasi-conformal transformation optics for energy concentration *(Invited Paper)*

Douglas H. Werner, Jeremiah P. Turpin, Donovan E. Brocker, Xiande Wang, The Pennsylvania State Univ. (United States); Zhi Hao Jiang, The Pennsylvania State University (United States); Pingjuan L. Werner, The Pennsylvania State Univ. (United States)

Transformation Optics (TO) has enabled new methodologies for the design and specification of gradient-index (GRIN) lenses for radio-frequency and optical applications by linking refractive index gradients to a mathematically equivalent change in geometry in another dimension. With the new mathematical design tools, there have been many interesting devices introduced in the literature, such as optical collimators and absorbers (optical “black holes”), GRIN couplers and bends for optical waveguides, and compressed or flattened collimating lenses for imaging and non-imaging applications. Many of the most interesting TO designs are not feasible for implementation, however, due to the complex anisotropic, inhomogeneous material parameters required by the full TO formulation. Instead, restricting the geometric transformations to be mathematically conformal or quasi-conformal (qTO) eliminates the anisotropic material requirements and allows implementation with an isotropic 2D or 3D GRIN profile, for which multiple fabrication methods exist in the RF and IR wavelength ranges and are in development for the complete optical spectrum. We present an overview of the usefulness of combining TO, qTO, and GRIN optics for energy concentration along with the associated design and analysis techniques.

Moving away from traditional lenses to GRIN and TO optics for which, in general, no analytical geometric optics or full-wave solution exists, involves the development of new design strategies for individual lenses and systems of lenses. We demonstrate results obtained using advanced, multivariate optimizations that are tightly coupled to a fast, advanced inhomogeneous ray tracing engine for electrically-large lenses, and to an efficient body-of-revolution solver for electrically-small cylindrically-symmetric lenses.

8834-15, Session 4

Design method for color-corrected layered spherical lenses

Narkis E. Shatz, John C. Bortz, SAIC (United States)

We consider the problem of designing imaging lenses consisting of thin, concentric, spherical annuli, each having a constant refractive index at a specified wavelength. For single-wavelength designs, we describe a recursive algorithm capable of generating the annular layer structure required to achieve arbitrarily low aberration levels, based on a specified structure of the outer layers. For the design of color-corrected lenses, we show how the single-wavelength design method can provide a parsimonious parametrization scheme that can be used in conjunction with a global optimization process to search for designs exhibiting minimal aberrations over the desired waveband of operation and that also satisfy design constraints.

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8834-16, Session 4

Engineering metacrystals and flat optics with Huygens, Fermat, Bragg, and Fresnel laws *(Invited Paper)*

Zeno Gaburro, Univ. degli Studi di Trento (Italy)

Novel perspectives are introduced by combining classical concepts, starting from Bragg interference, with metamaterials. How about combining polarization properties of meta-atoms with translational symmetry? How can glide planes be exploited in spectroscopy and in optomechanics? What can be said about impedance? I will address these questions and others. The battle horse will be a structure that generalizes classical Snell and Fresnel laws, based on “phase discontinuities”. I will finally outline some future challenges and opportunities.

8834-17, Session 5

Free-space optics for reconfigurable card-to-card optical interconnects

Ke Wang, Ampalavanpillai T. Nirmalathas, Christina Lim, Efstratios S. Skafidas, The Univ. of Melbourne (Australia); Kamal E. Alameh, Edith Cowan Univ. (Australia)

We proposed and experimentally demonstrated a 3?20 Gb/s free-space based reconfigurable car-to-card optical interconnect architecture for data-centers and high-performance computing. The proposed system employed low-cost VCSEL array as the transmitter and was based on free-space optical signal transmission, where the beams can be dynamically steered to different cards by MEMS-based steering mirrors to realize flexibility and reconfigurability. Compared with other beam steering mechanisms, MEMS-based mirrors have the advantages of simple tuning principle through signal reflection and high tuning efficiency by proper coating. Micro-lens arrays were also utilized to collimate the optical beams at the transmitter side and for signal focusing at the receiver side. Small-size printed-circuit-board (PCB) based optical interconnect modules were designed and fabricated. These modules used 1?4 VCSEL arrays as light sources and the VCSELs had a 3-dB electrical bandwidth of ~9.6 GHz. To increase the bit rate, VCSELs were directly modulated with 4-level carrierless amplitude and phase (4-CAP) modulation format (2 b/s/Hz spectral efficiency). With 2 mW transmission power, 3?20 Gb/s interconnect was realized for up to 30 cm card-to-card horizontal distance with a bit-error-rate (BER) of ~10-6. The reconfigurability was also demonstrated on both port- and card- levels with three different channel configurations characterized. Furthermore, the receiver sensitivity (at the BER of 10-9) of proposed scheme was measured and when the card-to-card horizontal distance was 20 cm, the worst-case sensitivity was shown to be better than -11.10 dBm. When the horizontal distance increased, the sensitivity became slightly worse, mainly due to the inter-channel crosstalk.

8834-18, Session 5

Freeform TIR collimators for the removal of angular color variation in white LED spotlights

Corien Prins, Technische Univ. Eindhoven (Netherlands) and Philips Electronics Nederland B.V. (Netherlands); Christine Schneider, Teus W. Tukker, Philips Lighting B.V. (Netherlands); Jan ten Thije Boonkkamp, Technische Univ. Eindhoven (Netherlands); Wilbert L. IJzerman, Philips Research Nederland B.V. (Netherlands)

Angular color variation in white, phosphor-converted LEDs is an urgent

problem in lighting. The color variation is caused by the conversion of blue light into yellow light by the phosphor layer, and therefore inherent to phosphor-converted LEDs. Spotlights using such LEDs show undesirable, yellow rings in the beam. LEDs can be modified to reduce the color variation, but this increases their cost and reduces their luminous efficiency. A better solution is to modify the surface shape of the collimator. We developed an inverse method to design collimators that completely remove the color variation for point light sources without the need of facets, holographic foils or scattering surfaces. The design procedure consists of two steps: first we construct transfer functions for the light from the source to the target, such that in the far field we have the required intensity and the color variation is removed. This is done using measured chromaticity and intensity data of the LED. Subsequently, we calculate the free surfaces of a collimator using the generalized functional method developed by Bortz & Shatz. We performed numerical simulations with the resulting collimators in the ray tracing program LightTools. We discuss the method, and show results of numerical simulations, where we take both ideal point sources and realistic light sources into account.

8834-19, Session 5

Advances in aplanatic optics for illumination

Lun Jiang, Roland Winston, Univ. of California, Merced (United States)

In a previous SPIE conference1 we presented a development in aplanatic design that can be traced back to Galileo, Newton and Descartes. In this presentation we show a design improvement that makes this more efficient and more affordable2. We now go even further back in time to Hypatia of Alexandria (335-405AD) who was arguably one of the greatest mathematicians of the ancient world.

8834-20, Session 5

Estimation of the flux collected by conic reflector patches

Cristina Canavesi, Univ. of Rochester (United States); William J. Cassarly, Synopsys, Inc. (United States); Jannick P. Rolland, Univ. of Rochester (United States)

The Oliker supporting ellipsoids algorithm for freeform reflector design builds a reflector from sections of conics, each of which redirects the light from the point source to a discrete target point. The design process consists of iteratively adjusting the optimization variables that control the size and shape of the conics, and evaluating the flux for each target point, until the desired target illumination is met within a set tolerance. The estimation of the amount of flux directed to each target required at each iteration step is currently a main limitation to the computation speed of the supporting ellipsoids algorithm. The target evaluation method also drives the accuracy of the reflector solution obtained. A common approach for estimating the flux collected by the reflector patches is to use Monte Carlo ray tracing, and the choice of the number or rays traced is a trade off between accuracy and speed.

We explore an alternative flux estimation approach by calculating the intersections between neighboring conics to find the boundaries of each conic patch. Once the perimeter of each reflector patch is known, it is possible to calculate the solid angle subtended to estimate the flux collected.

8834-21, Session 6

Multiple luminous intensity distributions by using a single freeform optical element

Michael Berens, RWTH Aachen (Germany); Adrien Bruneton, RWTH Aachen (Germany); Axel Baeuerle, Fraunhofer-Institut für Lasertechnik (Germany) and RWTH Aachen (Germany); Martin Traub, Rolf Wester, Fraunhofer-Institut für Lasertechnik (Germany); Jochen Stollenwerk, RWTH Aachen (Germany) and Fraunhofer-Institut für Lasertechnik (Germany); Peter Loosen, RWTH Aachen (Germany) and Fraunhofer-Institut für Lasertechnik (Germany)

In many mass-production applications of lighting design, the cost of manufacturing as well as compact design plays a vital role in addition to the desired function. Thus, the integration of multiple functions within a single part can be of economic and ecological benefit.

Previously (“Irradiance tailoring with two-sided, Fresnel-type freeform optics,” in Proc. SPIE 8485), we presented a freeform lens design achieving a compact form factor by segmentation of the output surface. In this paper, we show that by segmenting the input surface, the integration of multiple lighting functions in a single lens is possible. This is demonstrated for an automotive application.

Using the method based on the Monge-Kantorovich theory of optimal mass transport, two optical surfaces (input and output surface) that create a single light distribution are designed. The resulting surfaces are then used as a basis for the introduction of smaller, secondary input surfaces that are designed to use the original output surface. This results in a compact lens design that integrates the functions of a fog lamp and a daytime running lamp by switching of multiple LED light sources.

Furthermore, the efficiency of the individual light paths resulting from the multiple light sources as well as the overall efficiency of the system is analyzed. Finally, the point of manufacturability is touched.

8834-22, Session 6

Novel multi-layer remote phosphor linear optics for solid state lighting

Charles Edwards, Intematix Corp. (United States)

As LEDs move into general lighting developing high efficiency, optically uniform linear light sources is critical. Presented is a new linear light emitting optic designed to work with blue LEDs (450-460nm). The first white appearance remote phosphor combines a high efficiency phosphor down-converter layer with an integrated secondary optic in a single component. The optic is produced using co-extrusion creating different optical layers in a single component. The outer layer can be an integrated hi efficacy diffuser or linear lens depending on the application.

Technical results that will be presented:

- Systems design and efficacy with multi-layer remote phosphor. At 4000K CCT system efficacy of 120lm/WDC can be achieved.

- First true white appearance remote phosphor. Remote phosphor is conventionally yellow. We explain how white appearance is achieved with an integrated, hi efficacy outer layer. Test results show equal performance to single layer, yellow remote phosphor.

- Light uniformity. White LEDs in linear typically have “hot spots” over each LED. Aggressive diffusers, up to 15% loss. Most LED use large T8 size (1” OD) to improve uniformity. We show how this new architecture achieves uniform light with smaller OD and no 2ndary diffuser. Uniformity achieved with 12mm spacing in a compact T5 (5/8”) form factor.

- CCT from 2700K-5000K and CRI of 70CRI to >95 are achievable with the relative performance of different CCTs and CRIs being presented.

8834-23, Session 6

Light trapping in LED’s

Melissa N. Ricketts, Roland Winston, Univ. of California, Merced (United States); Julius A. Muschaweck, OSRAM GmbH (Germany)

The impressive progress in LED technology that has made LED's more efficient (lumens/watt) than common light sources, has encouraged investigation of potential advantages for creating a pleasing and productive environment. The effect of spectrum and variability are being studied is a controlled experiment.

8834-24, Session 6

Design and optimization of fiber lenses in plastic optical fibers for indoor illumination

Daniel E. Ceballos-Herrera, Perla M. Viera-González, Guillermo E. Sánchez-Guerrero, Gustavo Cárdenas-Ortíz, Valentín Gusmán-Ramos, Arturo Castillo-Guzmán, Romeo Selvas-Aguilar, Univ. Autónoma de Nuevo León (Mexico)

We present a numerical analysis of different fiber termination shapes in order to study the maximum numerical aperture that can be obtained in end emitting plastic optical fibers with diameters around 10 mm. Our analysis includes the modeling of angle polished fibers, conical lensed fibers, and wedged fibers with different lengths, angles and curvatures respectively. The optimization of these parameters allows us to obtain a maximum possible angle which the light can be emitted at the plastic fiber end. These results contribute to minimize the use of fiber components in luminaire systems which can be based in solar concentrators coupled to plastic optical fibers, and consequently it allows us to reduce their installation cost. We also analyze the light distribution of the emitted light and the optical tolerances of the parameters above mentioned to evaluate the performance of the optimized fiber lens. In addition, the effect of using gratings inscribed on the fiber lens surface is also discussed, and we explain how it can improve not only the emitted angle of the transmitted light, but also the amount of solar light coupled to the optical fiber. These results are of great interest for the improvement and design of compact luminaire systems based in optimized plastic fiber lens for indoor illumination.

8834-25, Session PMon

Far-field condition for OLED light sources

Wentao Cai, Xianming Liu, Peng Zhang, Weimin Chen, Chongqing Univ. (China)

Nowadays, white organic light emitting diodes (OLED) as the predominant light sources of the future are attracting much attention especially in the indoor lighting, due to the advantages of flexible, large area lighting, color tunable and high CRI, etc. In order to describe the light distribution properties of the OLED sources, the intensity under different azimuth angles should be obtained firstly. However, the light intensity definition is only applicable to point sources because the solid angle's vertex should be a point. For a real point source, the shape of the radiation pattern is independent of distance. The intensity is inversely proportional to the square of the distance from the source, which known as inverse square law. A light source can be modeled as a point source only if the detector is placed far enough away from the source. It is necessary to know where the far-field begins since most of the lighting designs are based on the far-field optical characteristics. In this paper, we deduce the far-field conditions for OLED sources with different continuous luminous area. The relative far-field distances (RFFD) for OLEDs with round, rectangular, annular, hemispherical and semicylindrical shapes are calculated. The RFFDs for LED arrays with the same size and light distribution are also given for comparation. Results show that the RFFDs for OLEDs are smaller than that of LED arrays with the same sizes. The classical five times rule is not applicable for all OLEDs with different luminous area.

8834-26, Session PMon

Analysis of far-field distance of LED arrays based on an improved error calculation formula

Wentao Cai, Xianming Liu, Peng Zhang, Weimin Chen, Chongqing Univ. (China)

Most of the lighting designs are based on the far-field characteristics of light sources. In the far-field region, a surface source can be modeled as a directional point source. For a point source, the illuminance E and the measurement distance d should satisfy the inverse square law. A surface source can be considered as a point source if the similarity from using the inverse-square law is higher than 99%. However, the results of where the far-field begin may be quite different with different similarity calculation formulas. In this paper, we calculate and compare the relative far-field distances (RFFD) of LED arrays with several commonly used similarity calculation formulas, such as the normalized cross correlation (NCC), cosine of vectorial angle (COS), constrained Pearson correlation(CPC), spearman rank correlation (SRC) and root mean square (RMS) weighted by the maximum value of the intensity at infinity. Results show that the weighted RMS is the most reasonable equation to define the far-field distance calculation error. Moreover, we propose the summing value but not the maximum value of the intensity as the weighting coefficient to define the RMS error, which can minimize the influence of the light distribution pattern of the light source. Finnally, the RFFDs of LED arrays of radiation patterns of Lambertain, concentrated-type and batwing are given with the proposed weighted RMS as calculation error.

8834-27, Session PMon

Quantitative comparison of photometric quantities for road lighting between CIE and IESNA standards

Shi LingNa, Chongqing Univ. (China) and Chongqing Jiaotong Univ. (China); Weimin Chen, Xianming Liu, Wei Lai, Chongqing Univ. (China)

There are two standard systems quantitatively defining the photometric quantities for road lighting, which are released by CIE (International Commission on Illumination) and IESNA (Illuminating Engineering Society of North America). The criteria definitions include the average road surface luminance, overall road surface luminance uniformity and longitudinal road surface luminance uniformity and so on, which are defined differently in the two standards. There were some reports analyzing these differences qualitatively. However, the quantitative description on these differences between CIE and IESNA standards has not been reported.

In this paper, we analyze the differences between CIE and IESNA standards quantitatively. Firstly, the backgrounds of the two road lighting standards are introduced. Secondly, the definition and computing method about the photometric quantities of the two standards are compared in detail. Finally, the road light distributions and photometric quantities are calculated based on CIE and IESNA standards in the case of several urban roads with different lanes and luminaries arrangement. These results indicate that the difference about illuminance between CIE and IESNA is very slight. However, the luminance, especially the longitudinal road surface luminance uniformity has obvious difference between the two standards.

8834-28, Session PMon

High efficiency decoupling lightguide with optical structure design

Jian-Fong Jhou, Jong-Woei A. Whang, Tzung-Han Lin, Kai-Cyuan Chan, National Taiwan Univ. of Science and Technology

(Taiwan)

According to the U.S. Green Building Council (USGBC), the quality green building has low energy consumption and comfortable lighting. In general, Natural Lighting Illumination System (NLIS) is a feasible solution to reach the quality green house. However, the optical design in NLIS may have some limitations and problems in light emission. In this paper, we propose a novel design to uniformly decouple the light. And it is able to solve light pipe problems. The design component has two major features. The first feature is to decouple the light from the light pipe and transmits the light simultaneously. The other is to keep the distribution of the light consistent after decoupling. According to the étendue conservation theorem, a perfect optical system produces an image with the same étendue as the source. Due to this reason, we design an optical decoupling structure whose shape is a trimmed cone with several cylinder branches. In the optical pipe, the decoupling light guide decouples the source light and delivers it to each branch efficiently. The branch structure is designed to be inserted into the side of the cone with a specific tilt angle. By adjusting the tilt angle and diameter for individual branch, the uniformity of light transmission is controllable. In order to have high transmission efficiency, we make the incident angle and the exit angle of the light beams consistent as possible. In our experiment, these parameters can be optimized for specific applications.

8834-29, Session PMon

Design and analysis of a mathematic module about compensation of color difference and color temperature in innovative solar concentrator

Ping-Kuang Chen, Hung-Shing Chen, Kai-Cyuan Chan, Jong-Woei A. Whang, National Taiwan Univ. of Science and Technology (Taiwan)

In recent years there are many studies and applications of solar energy. The purpose of it is to guide sunlight into buildings for illumination to achieve the goals of energy conservation and carbon reduction. The concentrators in Natural Light Illumination System (NLIS®) have excellent light collecting effects; however, in application of lighting, light ray after passing through NLIS® will produce color difference and variation of color temperature problem which will affect the quality of illumination.

In order to solve the problems of color difference and variation of color temperature, we simulate different correlated color temperature (CCT) of sunlight by multi-spectrum light source and focus on the analysis of color difference and variation of color temperature of NLIS®, constructing a mathematic formula of color temperature conversion with the goal of designing a mathematic model for light source compensation and correction.

This mathematic model can be used to calculate the compensation of artificial light source in NLIS® .Therefore we can achieve the best configuration accordingly to reach best effect and quality of illumination.

8834-30, Session PMon

High uniformity innovative of the mixed light coupling structure

Yi-Chun Lin, Jong-Woei A. Whang, Tzung-Han Lin, Kai-Cyuan Chan, National Taiwan Univ. of Science and Technology (Taiwan)

With the advance of science and technology, the green energy plays an important role for human living. The natural light, as one kind of illumination, provides the most comfortable experience for human eye's perception. In our previous works, the natural light guiding system has successfully transfer outdoor natural light into the indoor environment for energy saving and health purposes.

Due to the varying incident angle of sun light, energy and color temperature change overtime. When people are using natural light guiding system, it is necessary to monitor and maintain the quality of indoor lighting simultaneously in real time. However, the uniformity of the mixed light is a challenging issue and needed to be solved.

In this research, we focus on developing a novel structure which integrates two light sources. Traditionally, the integrating sphere and light pipes are used for mixing light. Different from that, our structure has the mixed light coupling function.

In this design, the nature light is initially transferred into this element, and then additional artificial light is mixed together for improving the uniformity. This mixing light element consists of the light guiding mechanism and compound parabolic concentrator(CPC) structure, which aims to make the light emitting angle adjustable. It is proofed that this design induces better light uniformity than our previous works. Since we partially use the artificial light, the color temperature and the light intensity are controllable as well.

8834-31, Session PMon

A wedge-shaped structure prism of static solar concentrator in natural light illumination system

Chen-You Wang, Kai-Cyuan Chan, Tzung-Han Lin, Jong-Woei A. Whang, National Taiwan Univ. of Science and Technology (Taiwan)

Natural light is one kind of inexhaustible and environment friendly energy. It is able to replace parts of traditional illumination by additional guiding designs. In this paper, we reveal a light guiding system which is able to efficiently collect and transmit the outdoor natural light. This system includes a solar concentrator, optical pipes and light emitters. To improve the efficiency of light collection, we focus on optimizing the arrangement and structure of wedge-shaped prisms. In the solar concentrator, many wedge prisms with specific angles are ingeniously arranged for reducing the number of junctions. This design will avoid energy loss and concentrate light beam during transmission.

Besides, we reveal a mathematical model to simulate the parallelism which is composed of various kinds of materials. We expect the compression of light intensity will be improved. Finally, the light is delivered to emitter via optical pipes for indoor illumination.

This guiding system has the advantages of the traditional solar concentrator in collecting light. It also reduces the complexity of traditional designs in light transmission and emission. Our design is cost efficient, and the experimental result shows its feasibility.

8834-32, Session PMon

High efficient solar tracker based on a simple shutter structure

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In many photovoltaic (PV) or sunlight-illumination systems, solar trackers are always essential to obtain high energy/flux concentration efficiency, and that would lead to increase cost and extra power consumption due to the complex structure and heavy weight of the trackers. To decrease the cost while without sacrificing efficiency, a Fresnel-lens concentrator incorporated with a simple and cheap shutter, which consists of high reflective acrylic mirrors instead of conventional trackers, is proposed in this paper to provide solar tracking during the daytime. Thus, the time-variant and slant-incident sunlight rays can be redirected to vertically incident upon the surface of the Fresnel lens by appropriately arranging acrylic mirrors and swinging them to the proper slant angles with respect to the orientation of sunlight. The computer simulation results show that a flux concentration efficiency over 90%, as compared with the efficiency

of directly normal incident sunlight, can be achieved with the mirror reflectance of 0.97 and for any solar incident angle within ±75 degrees to the normal of the Fresnel lens. To verify the feasibility and performance of the concentrator with the proposed shutter, a sunlight illumination system based on this novel structure is demonstrated. Both computer simulation and practical measurement results for the prototype of the sunlight illumination system are also given to compare with. The results prove the simple and high efficient shutter applicable to general PV or sunlight-illumination systems for solar tracking.

8834-33, Session PMon

Optical design for uniform color mixing illumination system

Peng Liu, Huihui Wang, Rengmao Wu, Yang Yang, Zhenrong Zheng, Haifeng Li, Xu Liu, Zhejiang Univ. (China)

In many applications, the emitting light from LEDs with different colors need to be mixed together on a large-scale target plane and this illumination mode is usually generated by a diffuser. Abandoning the traditional method, we proposed a LED color mixing method which can produce large-scale illumination with high color uniformity. This method can be divided into two steps: irradiance array scheme and design of LED lens. With this method, an independent rectangular irradiance distribution is generated by each lens unit, as many as LED lens units with different colors are integrated on a LED module unit and the large scale color uniform illumination is obtained by arraying the irradiance distribution produced by each LED module unit. Thus, the key to the method is to design a LED lens which can generate required irradiance distribution. By numerically solving a set of partial differential equations restricted by a mapping relationship, an initial lens model is obtained. However, the pattern generated by the initial lens is not a strict rectangle and a dark zone will occur at the joint of the neighboring illumination units. Considering the consistency of irradiance uniformity between the central area and the marginal area of the target plane, a merit function with the irradiance of the dark zone involved is adopted, optimization is conducted with the downhill simplex algorithm to obtain an appropriate lens model. By optimization, the irradiance uniformity is improved from 0.8907 (relative standard deviation, RSD) to 0.0773 in one example. At last, a 3?3 array of LED module units is designed, and a desired result with high color uniformity is obtained. This color mixing method is feasible and practical, and is superior to the existing methods.

8834-34, Session PMon

Stackable static solar concentrator with Hexagonal design

Chien-Cheng Su, National Taiwan Univ. of Science and Technology (Taiwan)

With the progress of modern technology, people begin to take the issues of environment protection and green energy seriously. Natural and healthy illumination becomes the same goal for mankind.

Sunlight collectors can be divided into two types: one is the active-form system which follows the sun's track based on the trajectory of sunlight and guides natural light into buildings for indoor illumination. Another is the passive-form system which has the features of low cost and eco-friendly without the needs of electrical power and control components, leading natural light directly into the indoor target areas.

This study proposes a new kind of passive concentrator. With the expansible characteristic based on the regular-hexagon design, as many as desired of the regular-hexagon concentrators can be stacked perfectly together to form a honeycomb-like static concentrator. The strength of this concentrator is that we can significantly increase the scope of the received light and expand the light receiving area freely. Moreover, we can utilize this characteristic to reduce the number of the optical fibers connected to the concentrators for transmission so to decrease the cost and bring a natural green illumination to human beings.

8834-35, Session PMon

A high efficiency plane lighting concentrator using round-shape prism structure to compress sunlight for indoor illumination

Chia-Min Lin, Jong-Woei A. Whang, Chun-Han Chou, Shih-Chi Tai, National Taiwan Univ. of Science and Technology (Taiwan)

In recent years, green energy has undergone a lot of development and has been used for many applications. Currently, energy-saving and carbon dioxide reduction are the most critical issues faced by the globe. Therefore, solar energy should be used as much as possible. Many research studies have focused on illumination with sunlight as a means of saving energy and creating healthy lighting. To create a low-cost collector that can be easily installed on a large building, we have designed a static concentrator to collect sunlight for indoor illumination. Prismatic elements are typical devices of natural light illumination system for redirecting and collecting daylight. Based on the principles of optics, this paper presents a new type mathematical matrix static solar concentrator. We collect sunlight using a plane round-shape concentrator, compressing light beams and transmitting light beams through a channel module from the export outlet of the concentrator, and we transmit the high-density light via optic fiber cable for indoor illumination. In addition, we define an optical energy density factor to calculate the value of the light gathering efficiency of the sunlight on the concentrator. This indicator shows the illumination of collected sunlight on the export side of the concentrator. Furthermore we design a prism reflection structure in the export, which could make the aperture of light channel smaller. We save 50% of optic fiber usage, but the efficiency remains. Our team has evaluated the concentrator's efficiency by the indicator. We have designed a high throughput plane lighting concentrator using round-shape stacked structure. This system will provide a great number of benefits for the people who use it.

8834-36, Session PMon

A static solar concentrator with hybrid multilayer stack structure for natural light illumination system

Chia-Min Lin, Jong-Woei A. Whang, Chun-Han Chou, Zong-Heng Sie, National Taiwan Univ. of Science and Technology (Taiwan)

Today, there is a shortage of the energy in the world. Green energy is the best alternative energy because there is low environmental impact and an unfailing supply. Besides, some renewable energy sources have geographical or environmental imit. In the recent years, Energy-saving and carbon dioxide reduction are the most critical issues currently faced by the globe. Therefore, in daytime, solar energy should be used as much as possible. In addition to the use of solar cell, daylight illumination is also an important access to solar energy. Our team designs a static concentrator with vertical stack structure. In general, static concentrators have better collection efficiency when sunlight just enters the concentrator perpendicularly. We design a compound curved surface which can increase collection efficiency for different sun's azimuth. And, we use prism and geometric structure to make sure that concentrated sunlight will achieve total reflection on each layer and transmit completely to port. The design can decrease the divergence angle and improve coupling efficiency with transmission system. Although new natural light illumination system can effectively guide collected sunlight and send it to the basement or to other indoor places. We have designed a static solar concentrator with hybrid multilayer stack structure to gather and concentrate the collected sunlight from the natural light. Our system can effectively deliver more than 60% energy transmission. We have designed, simulated, and optimized a light collection system, which our analysis shows equals the qualities of a traditional lighting system.

8834-37, Session PMon

High efficiency half-cylindrical Fresnel lens solar concentrator assisted by Cassegrain structure

Chia-Hsing Chu, Jong-Woei A. Whang, National Taiwan Univ. of Science and Technology (Taiwan)

Due to the energy crisis and enhancing awareness of environmental protection, many scientists have focused on the research of energy saving recently, and the application of sunlight has been one the most popular issues. There are two types of solar concentrators for the purpose of collecting sunlight: one is active and the other is dynamic. The dynamic concentrator moves following the track of sun to direct sunlight into buildings for indoor illumination; a static concentrator has the advantage of electricity-free, guiding sunlight directly into the target areas. The latter type not only is low-cost but also environmental friendly.

In this paper, we develop an innovative static solar concentrator, setting Fresnel lens according to the sun-track on a half-cylindrical surface for collecting sunlight of all angles to the same focal point, and we call it half-cylindrical Fresnel lens concentrator. Next we set a convex lens under the focal point to generate parallel light from the collected light to the output and set up a Cassegrain reflector structure around the half-cylindrical Fresnel lens concentrator to generate light beam by gathering the collected light to the output again to form a new cascadable solar concentrator combining two optical structures which not only considerably increase the light collecting efficiency but bring great advantages to natural light guiding systems and green illumination. To sum up , this new developed static solar concentrator is named high efficiency half-cylindrical Fresnel lens solar concentrator assisted by Cassegrain structure.

8834-38, Session PMon

New complex circular light concentrator applied to lamps design for the convergent light type with OLED light source

Wei-Shao Su, National Taiwan Univ. of Science and Technology (Taiwan)

Traditional light sources have been gradually replaced recently, people start to develop a new alternative light source, Organic Light Emitting-diode(OLED) which compared to other light source has advantages like light, thin and flexible, and OLED itself can be a display and light-emitting on both side of OLED, we can use these characteristics of OLED in application of illumination to design creative new lamps.

In my research, we design a much more collimation and centralized illumination instrument under satisfaction convergence light type of government rule and also thin sized. We do light source secondary optical design according to uniform surface Lambertian light-emitting type of OLED, we design a new complex circular light concentrator on the top of the OLED, this circular light concentrator is composed of a lateral array of prisms structure to collect light in each region and then guide to the center of circular disk. It can not only converge the large area light source and enhance the brightness of the center to 55.1%, but also reduce the amount of thickness. With the new light concentrator, OLED will have a higher level of application for illumination.

8834-39, Session PMon

Set of new wide-angle sun light collection component with high-efficiency

Tzu-Tun Liao, Jhong-Wei Huang, Kai-Cyuan Jhan, National Taiwan Univ. of Science and Technology (Taiwan)

Nowadays many Countries have focused on green buildings development. The U.S. Green Building Council (USGBC) defines that “a good green building must have lower energy consumption and comfort illumination”, so the natural light illumination system is considered a better illumination system than the artificial ones regarding color and health issues.

The core of natural light illumination system is the design of optical components for sunlight gathering. However, the focus of the optical component design is often limited to the incident angle of sun light and the direction of receiving light, which in result leads to the decrease of gathering efficiency because of the movement of sun. The goal of this study is to focus on the setting of light-receiving components which can break the limitation of the incident angle of sunlight by using a special pyramidal angle of curvature to design the optical component. It also greatly enhances the light gathering efficiency. The optical components can be joined together as a sunlight collecting sheet, four sheets as a collection group. The number of the group’s light output is decreased to one, which in result efficiently reduces the cost of the optical fibers needed for light transmission.

The new structure of the design is expected to replace the existing passive collection optical components on market place in the future. It can be posted on the roof to gather sunlight for indoor illumination and reduce energy consumption for the goal of green building.

8834-40, Session PMon

A complex design concluding collecting and transmitting subsystems for natural light illumination system

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The greenhouse effect is an increasingly serious environmental issue which has drawn much attention in the area of the environment protection. Therefore the development of green energy industry is imperative. Natural light illumination system is a novel and eco-friendly illumination system directing sunlight into buildings for illumination without the opto-to-electricity conversion, which can efficiently reduce the loss of the solar energy in the transition between different energy types. This system can be divided into three subsystems: 1) collecting subsystem; 2) transmitting subsystem; and 3) emitting subsystem.

A coupler is needed to reduce the loss of energy during the coupling of the three subsystems. The study designs a combination of collecting subsystem and transmitting subsystem. The light collecting components consists of two parabolic mirrors, using its optical properties, confocal both mirrors to transmit light into transmitting subsystem. The collecting subsystem collects light via a multi-reflection angle of reflection surface amending light track to the lens and focused through the lens of the optical properties, hitting the lens connected to the next collecting subsystem to achieve the demand of light transmission. In this design, the two subsystems are integrated and can reduce the loss in the transmitting process between the two subsystems without via the other coupling. This design enhances the efficiency of the natural light illumination system for the utilization of solar energy.

8835-1, Session 1

Accelerated optical polymer aging studies for LED luminaire applications

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There is a need in the lighting industry to design and implement accelerated aging methods that accurately simulate the aging process of LED luminaire components. In response to this need a robust, flexible and reliable system has being built to study the aging characteristics of optical polymer materials and it has been employed to study a commercially available LED luminare diffuser. The experimental system consists of a "Blue LED Emitter" and a working surface (hot plate). The "Blue LED Emitter" is composed of a mechanical assembly that holds the LEDs at a desired distance from the hot plate, the optical assembly that controllably spreads the blue light to regions of the working surface, and the thermal assembly which maintains near-room temperature of the active LEDs. The distance between the optical assembly and the hot plate is precisely controlled by micrometer heads and the LEDs are carefully calibrated as a function of power and distance from the optical assembly. Several improvements were made to the original design in order to increase the temperature homogeneity of the heating plate as well as quantifying and minimizing the local heating of the samples due to the blue light itself which was shown to substantially distort the intended temperature of the samples under investigation at high intensities. Results of the commercially available LED luminare diffuser studies are presented which include a discussion of transmission studies, accelerated factors related to the life of the luminare and aging effects.

8835-2, Session 1

Effect of heat and short-wavelength visible radiation on phosphor-embedded LED encapsulant

Prathika Appaiah, Nadarajah Narendran, Yiting Zhu, Yi-Wei Liu, Indika U. Perera, Rensselaer Polytechnic Institute (United States)

The application of the light-emitting diode (LED) in general lighting has grown steadily over the past several years. The most common approach to producing white light is by using a short-wavelength semiconductor such as gallium nitride with a layer of yttrium garnet (YAG:Ce) phosphor, which produces a broad spectrum light covering the visible range. In this phosphor-converted (PC) method, the phosphor is dispersed within the encapsulant surrounding the LED die. The degradation of the encapsulant and phosphor plays a vital role in determining the useful lifetime of the LED. In white LEDs the encapsulant material is usually epoxy or silicone. The phosphor-embedded encapsulant is subjected to short-wavelength radiation and heat from the LED chip. The objective of this study was to evaluate the effects of short-wavelength radiation and heat on the photo-thermal degradation of the LED encapsulant, which leads to LED light output degradation. In this study, light output degradation as a function of heat and irradiance for different phosphor concentrations in the encapsulant were analyzed. Color shift of the different samples subjected to photo-thermal degradation also was studied. This study will help give an understanding of the individual contributions of heat and short-wavelength radiation to reduced reliability of the LED package. The details of the experiment and the results will be presented.

8835-3, Session 1

Thermal management of the remote phosphor layer of an LED system

Indika U. Perera, Nadarajah Narendran, Rensselaer Polytechnic Institute (United States)

Generally in a white light-emitting diode (LED), a phosphor slurry is placed around the semiconductor chip or the phosphor is conformally coated around the chip to covert the narrowband, short-wavelength radiation to a broadband white light. Over the past few years, the remote-phosphor method has provided significant improvement in overall system efficiency by increasing the conversion rate. It has also shown to improve LED useful life by slowing lumen depreciation, since the phosphor layer is spaced apart from the hot LED die. However, increased light output and smaller light engine requirements are causing high radiant energy to be incident on smaller-footprint, remote-phosphor plates, thus heating the phosphor layer, especially when the phosphor material has low conversion efficiency. Phosphor layer heating can negatively affect performance in terms of luminous efficacy and life. In such cases, the performance of remote-phosphor LED lighting systems can be improved by suitable thermal management that can reduce the temperature of the phosphor-embedded encapsulant. As a solution to this problem, a perforated metal plate was embedded within the phosphor layer to remove the heat, and the parameters that influence the effectiveness of heat extraction were studied. These parameters include the metal-to-phosphor layer interface area and the surface finish of the metal plate. The temperature of the remote-phosphor encapsulant surface was measured using IR thermography. A reduction of temperature in remote-phosphor encapsulant surfaces was observed as the conduction area increased. The details of the experiment and the results will be presented.

8835-4, Session 1

Thermal behavior of phosphor in phosphor-converted white LED

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We investigated the optical and thermal characteristics of remote type light emitting diode packages as a function of location of phosphor layer. In order to fabricate the remote type package, a silicone-epoxy resin and mixture of resin and phosphor (YAG) were dispensed alternately on a bare package. The location of phosphor layer was able to be varied by controlling the dispensing time of a dispenser. The thickness and distance from the LED chip of the phosphor layer have been observed from SEM images. The junction and phosphor temperatures were determined by a thermal transient method and a direct thermocouple measurement, respectively. The phosphor temperature was always higher than the junction temperature, e.g. the junction and phosphor temperatures were measured to be 72.5 °C and 90°C, respectively when the phosphor layer-chip distance is 150?m. The difference was found to increase with the distance. Thermal simulation based on the finite volume model verified the experimental results and demonstrated that the thermal resistance between the phosphor layer and the LED chip is a major determinant of the temperature. Optical spectrum was measured using an integrating sphere, and showed that the optical power loss at the phosphor layer is in a range of 5 to 30 %. The conversion efficiency of phosphor was found to decline with temperature. While the remote type package was reported to extract more scattered photon, the optical output was found to decrease due to the poor thermal characteristics.

8835-5, Session 1

Accurate measurement of LED lens surface temperature

Indika U. Perera, Nadarajah Narendran, Yi-Wei Liu, Rensselaer Polytechnic Institute (United States)

Performance and reliability of high-power light-emitting diodes (LEDs) improve with better thermal management. In conventional white LEDs,

the chip is surrounded by an encapsulant with embedded phosphor particles. The increased heat in high-flux LEDs degrades the lens material and the phosphor, reducing overall performance and reliability. Past studies have shown large errors in temperature measurement when the temperature of an LED primary lens is measured with a thermocouple. This is mostly due to absorption of radiant energy by the thermocouple. The erroneous temperature measurement can cause problems during the design and measurement stages of LED luminaire development.
To understand the problem in using thermocouples to measure LED lens surface temperature and to find a solution, an experimental study was conducted. Infrared (IR) thermography was used as the reference temperature measurement in this study because its measurement values are unaffected by high radiant flux in the visible range. After studying the thermocouple wire metallurgy and its radiation absorption properties, a suitable material was identified to shield the thermocouple from visible radiation. A silicone elastomer with optical and thermal properties similar to the primary lens surface was used to maintain the thermal interface between the lens surface and the thermocouple sensing junction.
The deviation between thermocouple lens temperature measurement values and IR measurement values were within ±3 °C after adopting the radiation shielding method. The shielding layer was placed along the thermocouple lead wire and the thermocouple sensing junction was kept exposed. Experiment details and results will be presented in this paper.

8835-6, Session 2

Context-aware tunable office lighting application and user response

Nancy H. Chen, OSRAM SYLVANIA Inc. (United States); Jason Nawyn, MIT Media Lab. (United States); Maria R. Thompson, Julie Gibbs, OSRAM SYLVANIA Inc. (United States); Kent Larson, MIT Media Lab. (United States)

Multiple color channel LED lighting fixtures allow tuning of both intensity and color. Consequently, highly tailored lighting can be applied according to user needs and preferences. Besides improving performance, energy use can also be reduced since the brightest illumination is applied only when necessary. In an example application, low-activity or vacant areas of a 5-zone office are lit by low energy illumination, which can reduce energy consumption to 25-65% compared to typical full-time, full-brightness, office-wide illumination. The availability of color also allows communication functions (vacancy status, do not disturb) and additional aesthetic design possibilities. To reduce user burden in frequent switching between various illumination settings, an activity recognition sensor network is used to identify various office activities. The illumination is then adjusted automatically to satisfy the instantaneous needs of the occupants. A handheld mobile device provides an interactive interface for specifying user illumination preferences and gathering feedback regarding user impressions. Activity-triggered queries collect contemporaneous feedback that reduces reliance on memory; immediate previews of illumination preference options are also provided. Through mobile queries and post-experience interviews, user feedback was gathered regarding automation, colored lighting, illumination preferences, query method, and activity recognition accuracy. As might be expected, user impressions to automation and colored lighting were quite varied, as indicated by response words such as fun, pleasant, appropriate, satisfactory, distraction, isolated, and unfamiliar. Not surprisingly, individual color preferences affected user satisfaction. Positive reaction from a meaningful, though not universal, fraction of users indicates reasonable application potential, particularly as personal preferences and control are accommodated.

8835-7, Session 2

Color preferences revealed by statistical color rendition metrics

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The statistical metric of color rendering uniquely quantify the characteristics of color quality of illumination. Our color rendition engine [1] based on the statistical metric of color rendering allows for the subjective assessment of color rendition preferences by continuously changing the tetrachromatic color blend from dull to saturated at different correlated color temperatures. We now report on using the color rendition engine for revealing individual and cultural differences in color quality preferences. The research using 300 American and Chinese graduate students demonstrated that the majority of individuals preferred the color blend with the same statistical figures of merit on the average but with a much larger spread of blends for Americans. For both groups, the color rendition preferences depended on the object being illuminated. This was demonstrated by illuminating a set of common colored objects and three different paintings. We conclude that the color quality of lighting can be optimized using the feedback to change the spectral power distribution of the illuminating source depending on the needs of an individual observer and on an object being illuminated as was proposed in [2].

[1] A. ?ukauskas, R. Vaicekauskas, P. Vitta, A. Tuzikas, A. Petrulis, and M. S. Shur, “Color rendition engine,” Opt. Expr. 20, 5356?5367 (2012).

[2] M. Shur and R. Gaska, US Patent 7,235,766 (2007)

8835-8, Session 2

Intensity ratios of multicolor LEDs for optimal lighting performance

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Multicolor LEDs offer real-time color tunable control of light emission as never before in history. Given a set of available colored LEDs with known specifications, many possible combinations of relative light fluxes produce the same correlated color temperature (CCT). But only one combination maximizes luminous efficacy and color rendering index. In this work, simple formulas are given for the optimal intensity ratios of colored LEDs as a function of peak wavelengths, bandwidths, and CCT. In other words, a simple empirical and phenomenological model gives the relative light fluxes of LEDs in order to achieve the highest luminous efficacy and color rendering index for different CCTs. The model is constructed from numerical results reported in literature and some other calculations.

8835-9, Session 2

Phosphor crystals for tailored spectrum LEDs

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The pc-LED architecture is most suitable for creating a wide gamut of tailored full spectrum miniaturized artificial light sources. However, there are many challenges in developing tailored full spectrum light sources that could meet both the human factors and the energy saving gains simultaneously. The research on phosphor crystals are motivated for designing future lighting systems by using fundamentally different color conversion architectures than what is used in current commercial LEDs. The usage of optically clear (non-scattering) phosphor substrates or thin films will enable efficient ways for spectrum generation, reduced loss of optical power (that occurs by multiple scattering events within the powder phosphor regions in current pc-LEDs), reduced thermal quenching properties as well as reduced environmental degradation of the well known high efficiency phosphors. The development of crystal growth processes for phosphor alloys from high temperature melt and flux will be presented. Classes of phosphor compounds being researched include: broad band phosphors such as thiogallates (SrCaMgBa)Ga2(SSe)4:Eu2+, Ce3+, alloyed sulfides and selenides (SrCaGa)(SSe):Eu2+ Ce3+ , silicates (Ba1-x-ySrxCay)SiO4:Eu2+ , garnets

(YAG: Ce3+ micro-crystals, oxynitrides Lix(MgSrCaBa)ySiAlON: Eu2+, Ce3+ types and narrow emission phosphors such as tungstate and molybdate types [(SrCaMgBaYGdLa)x(WMo)yOz:Eu3+, Ho3+, Dy3+, Pr3+, Sm3+, Tb3+. Our studies have shown that melt and flux grown phosphor crystals exhibit many interesting features compared to solid state synthesized powders such as (a) higher excitation efficiency, (b) extension of charge transfer bands from UV to the blue regions, (c) reduced degradation with moisture exposure, etc.

8835-10, Session 2

LED champing: statistically blessed?

Zhuo Wang, OSRAM SYLVANIA Inc. (United States)

LED champing (smart mixing of single LEDs to match the desired color and lumen output) and color mixing strategies have been widely used to maintain the color consistency of light engines. The light engines with champed LEDs can easily achieve a color consistency of a couple MacAdam steps with widely distributed LEDs to begin with, i.e. the chromaticity of the light engines is visually matched. For many critical applications such as the merchandise lighting, the champed LEDs are proven to perform similarly compared to the fine binned LEDs.

From a statistical point of view, the distributions for the final color coordinates and the flux are studied. Several different distributions, including the Gaussian distribution and uniform distribution are assumed in the study. The results show it is not always true that the final color coordinates will have a tighter distribution after champing. Based on the analyses, the final distribution for the color coordinates as well as the flux values can be approximated with Gaussian for a large number of LEDs. The means and the standard deviations for the color coordinates and the flux are derived, which can work with the strategies for process improvement such as Six Sigma and are instrumental to the mass production quality control.

8835-28, Session PMon

Optical design for adjustable LED projection light with high utilization factor and uniformity

Yi-Chien Lo, Jhih-You Cai, Ming-Siou Tsai, Che-Chu Lin, Chong-Jhih Jiang, Ching-Cherng Sun, National Central Univ. (Taiwan)

In this paper, we present a new design, for LED projection light which can adjust its pattern size. The optical system is composed of a reflector and a lens. The pattern with high uniformity can be found in not only wide illumination but also narrow mode. Then, it also have high optical utilization factor. Furthermore, its performance is demonstrated by several measurements.

8835-29, Session PMon

Optical design of bicycle headlamp with low and high beam based on white LEDs

Jhih-You Cai, Yi-Chien Lo, Ming-Siou Tsai, Che-Chu Lin, Chong-Jhih Jiang, Ching-Cherng Sun, National Central Univ. (Taiwan)

In this research, we designed a bicycle headlamp, which provided the low beam and the high beam in different modes. Most of the users care about these condictions. In the two modes, one was good lighting on the roadway and met the K-mark regulation; the other one was high-density energy of light pattern. Before the optical design, we build a precise optical model for a high power LED produced by CREE in mid-field verification to make sure the accuracy of our simulation. After optical model of the LEDs, We used multiple-reflective surfaces to perform the low beam based on a high-power chip white LED. Some of the reflective surfaces made a high-contrast cut-off line light pattern on a plan at a distance of 10 m, while others created a uniform light pattern and illuminated the region of the K-mark regulation on the roadway. In the high beam mode, we used the other LED as a light source. We also used a reflector and lens to collect and project the light, which enhanced the central illumination on a plan at a distance of 10 m. Finally, we finished our secondary optics of bicycle headlamp with low and high beam.

8835-30, Session PMon

Effects of pitch and angle of the asymmetric optical diffraction component for LED fog lamp

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Light-Emitting Diodes (LEDs) have the advantages of small size, long lifetime, fast response time (?s), low voltage, good mechanical properties and environmental protection. Furthermore, LEDs could replace the halogen lamps to avoid the mercury pollution and economize the use of energy. Therefore, the LEDs could instead of the traditional lamp in the future and became an important light source. The proposal of this study was to investigate the effects of pitch and angle of the asymmetric optical diffraction component for a LED fog lamp. The novelty LED fog lamp was assembled of a reflector and an optical transparent differential component. The optimized design of the pitch and angle of the asymmetric transparent differential component was simulated by TracePro software. The design results must meet the standard of European regulations of ECE R19 Class F3. The pitch of asymmetric diffraction component was studied from 1mm to 6mm. The angle of the triangle structure of every pitch was modulated by the stray light from 5 to 32 degrees far from the center of diffraction component. The angle variant resulted from the light projection of the triangular structure of different pitch's position. The simulation results exhibited the optimal pitch is 5 mm by the best total luminous flux and the luminous efficiency. The optical efficiency could reach to 90% by the 92% reflection rate of the reflector. Also, the stray light could to meet the ECE R19 Class F3 regulation. Final, the experimental result of the pitch of 5mm diffraction component mockup could match the simulation result.

8835-31, Session PMon

Investigation of color temperature of high power white LEDs array modulated by mixing of monochrome or bicolor LEDs

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The advantages of light-emitting diodes (LEDs) have the small size, long life time, low power consumption, no UV-IR light, wide range of color temperature, fast-switching response and mercury-free etc. Furthermore, LEDs could tune light intensity by digital modulation for the life. Therefore, LEDs would replace traditional light source in the future. The proposal of the study was investigated the variation of color temperature in a high power light-emitting diodes (HP-LEDs) array modulated by monochrome or bicolor LEDs for intelligent lighting. The HP-LED was used a 3 Watt LED and the LED array was 3?3 square modulation was tuned by 3W red or yellow LEDs. There are three LEDs array: 5W(white)+4R(red), 5W+4Y(yellow), and 5W+2R+2Y were assembled in the research for the investigation of color temperature. The experimental results exhibited that 5W+4R LEDs array had the broader range of color temperature from 8000 K to 3000 K than the short range of 5W+4Y LEDs array from 8000 K to 5000K. In additional, the color temperature of 5W+2R+2Y LEDs array could adjust broadened color temperature range from 8000 K to 3000 K and improve the steep status of color temperature of 5W+4R LEDs array. However, the 5W+2R+2Y LEDs array is a good choice for the color temperature adjustment in the LED street light.

8835-32, Session PMon

Adjustable and automated system to obtain 3D photometric patterns

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A complete adjustable and automated system has been developed on the base of four blocks: the first one is the mechanical and adjustable structure, which is composed by a mobile base and a rectangular arc, where the photo-detector is located. The structure describes semi-spherical trajectories by means of two stepper motors.

The second stage corresponds to the automation of the structure movements. For controlling the motors and data acquisition, a microcontroller is employed that in turns helps keeping the cost of the overall system low. One of the stepper motors is located on the lateral axis of the device; that displaces the sensor along a semi-circular trajectory of 170°, almost half meridians; the other one is located at the base of the illumination source, which enables it to realize an almost complete rotation around its axis. The precision is increased with two rotation sensor located on the opposite side of the arc and on the mobile base. Additionally, before the data obtained from the photo-detector arrive to the microcontroller, a stage of signal conditioning is realized.

The third block corresponds to the voltage source, with the capacity to satisfy all energy requirements of the system. This stage is necessary in order to obtain a simple handling system, and to avoid the use of different voltage sources.

Finally, the last stage is formed by the graphical interface. The communication protocol between the data acquisition stage and the computer is USART. The graphical user interface (GUI) is developed using C#.

8835-33, Session PMon

Evaluation of optical and chromatic properties under electrical and thermal coupling in solid state lighting systems

Han-Kuei Fu, Yi-Ping Peng, Chien-Ping Wang, Hsin-Chien Chiang, Tzung-Te Chen, Chiu-Ling Chen, Pei-Ting Chou, Industrial Technology Research Institute (Taiwan)

For energy-saving, high efficiency and low pollution, the lighting of LED systems is important for the future of green energy technology industry. The solid state lighting becomes the replacement of traditional lighting, such as, light bulbs and compact fluorescent lamps. Because of the semiconductor characteristics, the luminous efficiency of LEDs is sensitive to the operating temperature. Besides increasing the luminous efficiency, effective controlling electricity and thermal characteristics in the design of LED lighting products is the key point to achieve the best results. LED modules can be combined with multi-grain process or through a combination of multiple LED chips. Accurate analysis of this LED module for the electrical, thermal characteristics and high reliability is the critical knowledge of modular design. In this report, we studied the electrical and thermal coupling phenomenon in solid state lighting systems to analyze their reliability. By experiments and simulations, we obtained the apparent variation of temperature distribution of LED system due to differences of their forward voltages and thermal resistances. These events may reduce their reliability. Besides, the evaluation of optical and chromatic properties was based on the variation of temperature distribution and current of LED system. This is the key technology to predict the optical and chromatic properties of LED system in use.

8835-34, Session PMon

The low-frequency noise spectrum analysis of the reliability of the InGaN LED

Tzung-Te Chen, Chun-Fan Dai, Chun-Wen Chu, Han-Kuei Fu, Chien-Ping Wang, Pei-Ting Chou, Industrial Technology Research Institute (Taiwan)

In recent years, with extensive use of InGaN LED, how to assess the LED quality and further improve LED reliability is very important. In this report, the noise spectrum measurement techniques were used to assess the amount of defects in the InGaN LED devices and compare with its ESD tolerance test result. The source of low-frequency noise are attributed to the carrier number or mobility fluctuation. It is because the carriers are randomly trapping-detrapping in defect states near the interface of the semiconductor. Thus, the testing LED sample with lower defect density can exhibit lower noise power spectrum density and higher ESD tolerance. Experimental results show that the low-frequency noise spectrum measurement is more effectively distinguish the LED device reliability than the current voltage curve measurement. EMMI?SEM and TEM images show that the noise source and the cause of ESD failure of the LED device are attributed by the poor quality of the SiO2 and ITO interface.

8835-35, Session PMon

Long-term lumen depreciation behavior and failure modes of multi-die array LEDs

Asiri Jayawardena, Daniel Marcus, Nadarajah Narendran, Rensselaer Polytechnic Institute (United States)

Multi-die array light-emitting diodes (LEDs) are becoming more common in the marketplace for use in illumination applications. One of the main advantages of such packages is that the overall footprint of the LED package is small for the amount of flux produced. However, a challenge for using such a product in lighting fixture applications is the heat density and the thermal management strategy needed to keep the LED junction temperature low for reliable performance. Array configurations, such as series parallel arrangement for stringing the LED dies, also can greatly affect the long-term performance. Therefore, another challenge is the reliability of the array that allows all dies in the package to behave similarly over a long period of time. To study lumen depreciation and conduct failure mode analysis, several multi-die array samples from different manufacturers were subjected to a life test. The products were tested at the maximum case (or pin) temperature reported by the respective manufacturers. Each LED package was attached to a temperature-controlled heat sink to maintain a constant operating temperature over the test period. All LED packages were powered at 700mA DC current. The LED case temperature, voltage, and current were continuously recorded at 4 hour intervals. Each sample was tested in an integrating sphere periodically to obtain luminous flux and chromaticity values. The photometric quantities of the LEDs were measured under pulsed current condition so that the junction temperature was close to room temperature. The details of the experiment and the results will be presented.

8835-11, Session 3

LED-based automotive forward lighting: status and challenges *(Invited Paper)*

Takayuki Yagi, Masaru Sasaki, Koito Manufacturing Co., Ltd. (Japan)

Six years after the introduction of LED headlamps launched in 2007, its penetration has now been rapidly expanded. The first production LED headlamp had power consumption of 50W and weighs 1600 grams for a low beam unit. By 2011, the progress was made to have power and

weight reduction to 25W and 400 grams respectively. The innovation continues.. This presentation shows what has been accomplished and where it is going with LED-based automotive headlamps. In particular, it describes the technical challenges and achievements for LED light sources, thermal management, optical design, electronics design, and system level optimization.

8835-12, Session 3

Data format standard for sharing light source measurements

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Illumination design requires accurate characterization of light sources for computer aided design (CAD) software. Various methods have been used to model sources, from accurate physical models to measurement of light output. It has become common practice for designers to include measured source data for design simulations. Typically, a measured source will contain rays which sample the output distribution of the source. The ray data must then be exported to various formats suitable for import into illumination analysis or design software. Source manufacturers are also making measurements of their products and supplying CAD models along with ray data sets for designers. The increasing availability of data has been beneficial to the design community but has caused a large expansion in storage needs for the source manufacturers since each software program uses a unique format to describe the source distribution.

In 2012, the Illumination Engineering Society (IES) formed a working group to understand the data requirements for ray data and recommend a standard file format. The working group included representatives from software companies supplying the analysis and design tools, source measurement companies providing metrology, source manufacturers creating the data and users from the design community. Within one year the working group proposed TM-25 file format which was sent to IES for consideration.

This paper will discuss the process used to define the proposed format, highlight some of the significant decisions leading to the format and list the data to be included in the first version of the standard.

8835-13, Session 3

LED light recycling using double prisms

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A novel LED recycling scheme using double prisms is presented. Two identical triangular prisms, one cross-stacked on top of the other, are tight-fit into a mirrored light tunnel. The whole prism/light tunnel assembly is then mounted on top of an LED source, whose emitting area is the same as that of the base plane of the said prism/light tunnel assembly. Each prism acts as a tapered-down light guide in one dimension, which selectively retro-reflects high-angle light along that direction. The outer light tunnel serves as a mirrored wall that folds back any light that escapes outside the two prisms. For a given collection cone angle, the height of the two prisms is optimized using ASAP, a commercial ray-tracing software. Preliminary simulation and experimental results show promise in significantly increasing the brightness of the LED sources within the collection cone. Specifically for a 4x recycling ratio a 70% recycling gain in center illuminance has been achieved (i.e., illuminance measured in the forward direction). This scheme has advantages over previous recycling configurations due to its compactness and ease of mounting. For example, compared to Wavien's spherical reflector approach that has been previously published, the current recycling configuration is much smaller in size because instead of fitting a much larger mirrored reflector on top of the LED source, this time we're using a structure that has the same lateral dimensions as those of the LED source itself. Further improvement is also possible if optimization of various system parameters is carried out.

8835-14, Session 3

System design of a LED based gobo projector

Henning Rehn, OSRAM AG (Germany)

In the contribution we discuss the relationship between etendue and luminous flux of gobo projectors and its implications on illumination design and system architecture.

On the basis of a given projector specification, a suitable LED type can be chosen and the number of needed LEDs and the necessary system etendue can be calculated. In a next step, we show how to design a suitable illumination system with primary and secondary optics and possibly including a homogenizer. Furthermore, implications for the design of the projection lens are discussed.

8835-15, Session 4

Design of LED edge-lit light bar for automotive taillight applications

Jyh-Cheng Yu, Jia-Hao Chen, Shih-Chiang Liu, National Kaohsiung First Univ. of Science and Technology (Taiwan)

This study investigates the optical design of LED edge-lit curved light guide bar and applies to the design of automotive taillight. LEDs have been widely used in automotive lighting. However, the designs are mostly of direct backlight using arrays of LEDs with diffusive patterns above, which often causes problems such as low uniformity, glaring, and too many LEDs required. Edge-lit light guide devices have been widely used in the back light models of LCD. However, the geometry of the lighting devices in the automotive lighting is often curved, and the literatures regarding the design of curved light guide components are very limited. This study addresses the design of edge-lit curved light guide bars and the optimization scheme for uniform light emitting. An automotive taillight with LED edge-lit light bar is used as an illustrated example. The light tracing software, TracePro is used to simulate the optical characteristics of the proposed design. 90° V-cuts are used as the optical features to distribute the light, and the lead angles of the v-cut are varied to achieve the optimum axial luminous intensity. A Fuzzy optimization scheme is proposed to manipulate the anchor spacing points which continuously varies the v-cut spacing along the light bar to satisfy the requirements of Society of Automotive Engineers (SAE) regulations and the illumination uniformity requirements. This study also proposes a solution to reduce the illuminance difference between the inside and the outside of the curved section of a light bar by varying the inside and the outside thickness of light bar.

8835-16, Session 4

Effect of a light guide plate with lenticular-arrayed surface on optical output for backlight and illumination application

Tun-Chien Teng, Li-Wei Tseng, National Taiwan Normal Univ. (Taiwan)

In this paper, we investigated the optical output characteristic of the light guide plate (LGP) with microstructures engraved by a CO2 laser, which is for edge-lit backlight of liquid crystal display or illumination. Especially, the laser-engraving method is suitable for the slim large-area LGP used in LED TV backlight, and the engraved microstructure has polish surface to contribute to better optical efficiency. For higher optical efficiency, we adopted a LGP with lenticular-arrayed surface as an experimental sample. In this case, we used the laser to engrave different kinds of microstructures directly on the flat surface (opposite to the lenticular-arrayed surface) of the bare LGP, respectively. The sample LGPs were measured for spatial and angular luminance by the BM7 and Conoscope. We further compared the results with the flat LGP without lenticular-arrayed surface in order to obtain the optimal design by evaluating the effect of lenticular-arrayed surface on optical output for different kinds of microstructures. The experimental data show the peak intensity in the normal increases by 5~20% for different conditions as compared to the flat surface LGP. In addition, the simulation results were also compared to the experimental data.

8835-17, Session 4

Diffraction gratings for lighting applications

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Sub-micron diffraction gratings have been used for two illumination application. One is to create a transparent see-through luminaire which can be used to illuminate and read a paper document. A second is a light sensor that can be used in a feedback loop to control a multicolor LED lamp. Optical design and prototypes are presented.

Diffraction gratings are demonstrated as light extraction features for light guide-based luminaires. A potential advantage is that these features are invisibly small and the light guide luminaire can have protective scratch-resistant claddings. Transparent luminaires for paper reading are designed using diffraction gratings with a pitch between 250nm – 700nm. Details of the gratings are designed with GSolver, a program that implements the RCWA-analysis approach. Results are then imported into a ray tracing program (LightTools) to complete the full system design.

Prototypes of a luminaire with a grating pitch of 275nm are fabricated by replication of a master grating onto glass light guide using Surface Conformable Nano-Imprint Lithography. Light from RGB-LEDs is injected into the light guide and extracted by the grating. The measured angular distribution compares well with the designed one.

A second application is a color sensor for an RGB-LED color luminaire. It is a transparent cover plate where locally a diffraction grating is manufactured using laser lithography. It acts as a light guide where a small fraction of the light is coupled in via a 425nm grating and guided to a sensor at the edge of the cover plate. In this way a single sensor can sample the full area of the RGB-luminaire and control the color non-uniformities.

8835-18, Session 4

Thermal and optical aspects of glob-top design for phosphor converted white LED light sources

Christian Sommer, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Paul Fulmek, Johann Nicolics, Technische Univ. Wien (Austria); Susanne Schweitzer, Wolfgang Nemitz, Paul Hartmann, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Peter Pachler, Hans Hoschopf, Franz Schrank, Tridonic Jennersdorf GmbH (Austria); Gregor Langer, Austria Technologie & Systemtechnik AG (Austria); Franz-Peter Wenzl, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria)

For a systematic approach to improve the white light quality of phosphor converted light-emitting diodes (LEDs) for general lighting applications it is imperative to get the individual sources of error for color temperature constancy under control. In this regard, it is important to understand how compositional, optical and thermal properties of the color conversion elements (CCE), which typically consist of phosphor particles embedded in a transparent matrix material, affect the constancy of a desired correlated color temperature of a white LED source under operation. In this contribution we use an LED assembly consisting of an LED die mounted on a printed circuit board by chip-on-board technology and a CCE with a glob-top design on the top of it as a model system and discuss the impact of the CCE shape, size and composition on the respective tolerance ranges for color temperature constancy with respect to substrate reflectivity and thermal load of the CCEs. From these studies, some general conclusions of optimized glob-top designs in regard of color temperature constancy of white LED sources under operation can be drawn.

8835-19, Session 4

Object-oriented emission adaptive phosphor layer for pc-white LED

Kwang-Cheol Lee, Deok Gi Kim, So-Ra Gang, Jong Hyeob Baek, Korea Photonics Technology Institute (Korea, Republic of)

Phosphor layer which basically absorbs a part of exciting light and emits the complementary light to white light is necessary for phosphor-converted white LED. Especially, phosphor layer for illumination requests not only high luminous efficiency, robust reliability in performance but also high color-rendering, high angular color homogeneity in quality.

In this study, we manipulated diverse structures into transforming the light emitted from LED chip into the modified emission pattern and made the optical structure from photosensitive resin with this emission pattern. Therefore, this optical structure could realize the object-oriented emission pattern. Phosphor particles could be arranged on the surface of LED chip or in/on the optical structure and combined with others. In conclusion, this emission adaptive phosphor layer could realize high rendering-color, luminous efficiency, angular color homogeneity and form an object-oriented emission pattern.

8835-20, Session 5

Insights into accelerated aging of SSL luminaires

Lynn Davis, RTI International (United States)

The lumen maintenance behavior of SSL luminaires must be addressed at the optical systems level, taking into account the aging characteristics of all components including LEDs, lenses, diffusers, and reflectors. While SSL products are often intended to have product lifetimes of 15 years or more, the rapid change in SSL technology has created a need for accelerated life test that can be performed in the span of several months. The accelerated aging protocols that we have investigated were derived from standard electronics industry tests and consist of variations in temperature, humidity and/or electrical power cycles. Some testing procedures were found to successfully accelerate lumen depreciation by broadly impacting the performance of the optical system including accelerating LED lumen depreciation, decreasing lens transmittance, and reducing housing reflectance. A strong dependence upon both optical material choices and luminaire design was also found. In some designs, LED lumen depreciation accounted for less than half of the total luminaire light loss during testing, with changes in the rest of the optical system dominating. Subtle differences were also found for luminaires using remote phosphor technology compared to those with conventional phosphor-converted LED and hybrid LED configurations. The findings from this study will be reported along with the insights that these tests provide on potential accelerated testing protocols for SSL luminaires. Emphasis will be placed on lumen maintenance as the pass/fail criterion, but color shift, as influenced by aging of the optical system, will also be discussed.

8835-21, Session 5

Prediction of L70 lumen maintenance and chromaticity for LEDs using extended Kalman filter models

Pradeep Lall, Junchao Wei, Auburn Univ. (United States); Lynn Davis, RTI International (United States)

Solid-state lighting (SSL) luminaires containing light emitting diodes (LEDs) have the potential of seeing excessive temperatures when being transported across country or being stored in non-climate controlled warehouses. They are also being used in outdoor applications in desert environments that see little or no humidity but will experience extremely high temperatures during the day. This makes it important to increase the understanding high temperature exposure effects on LEDs. The LEDs continually degrade and the light output decreases eventually below useful levels causing failure. Presently, the TM-21 test standard is used to predict the L70 life of SSL Luminaires from LM-80 test data. The TM-21 model uses an Arrhenius Equation with an Activation Energy, Pre-decay factor and Decay Rates. The underlying TM-21 Arrhenius Model may not capture the failure physics in presence of multiple failure mechanisms. In this paper, Kalman Filter (KF) and Extended Kalman Filters (EKF) have been used to develop a 70-percent Lumen Maintenance Life Prediction Model for a LEDs used in SSL luminaires. Ten-thousand hour LM-80 test data for various LEDs have been used for model development. System state at each future time has been computed based on the state space at preceding time step, system dynamics matrix, control vector, control matrix, measurement matrix, measured vector, process noise and measurement noise. The future state of the lumen depreciation and chromaticity has been estimated based on a second order Kalman Filter model and a Bayesian Framework.

8835-22, Session 5

The impact of different current driving schemes on the thermal load of the color conversion elements in phosphor converted LEDs

Franz-Peter Wenzl, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Paul Fulmek, Technische Univ. Wien (Austria); Christian Sommer, Paul Hartmann, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Peter Pachler, Hans Hoschopf, Franz Schrank, TridonicAtco Optoelectronics GmbH (Austria); Gregor Langer, Austria Technologie & Systemtechnik AG (Austria); Johann Nicolics, Technische Univ. Wien (Austria)

Correlated color temperature constancy and correlated color temperature maintenance are key issues in the context of the utilization of light-emitting diodes (LEDs) for general lighting applications. For a systematic improvement, it is imperative to understand how compositional, optical and thermal properties of the color conversion elements (CCE), which typically consist of phosphor particles embedded in a transparent matrix material, affect the constancy of a desired correlated color temperature of a white LED source under operation. In particular, a strong thermal load of the CCEs under operation may cause notable color shifts. By means of a combined optical and thermal simulation procedure, in this contribution we give a comprehensive discussion on the impact of different current driving schemes on the thermal load of the CCEs of phosphor converted LEDs. We show that on the one hand a decreasing duty cycle under pulse width modulation driving conditions may have a notable impact on the thermal load of the CCEs in comparison with DC current driving conditions of the same current amplitude and on the other hand also effects due to the non-linearity between the blue radiant flux and the current have to be considered.

8835-23, Session 5

A driving scheme to reduce AC LED flicker

Jianchuan Tan, Nadarajah Narendran, Rensselaer Polytechnic Institute (United States)

Light flicker is a common but unwelcome phenomenon in conventional lighting applications. In solid-state lighting, driving or dimming methods also give rise to light flicker. AC LED products in today's marketplace suffer from flicker, which stems from the arrangement of the micro-LEDs and the driving method. Research has shown that light flicker can be a health hazard to humans. Several solutions have been proposed to reduce light flicker in solid-state lighting applications; however, most have drawbacks in terms of power and other performance. This paper proposes a circuit design to reduce light flicker from AC LEDs while maintaining a normal power factor and high power efficiency. The circuit is composed of one resistive branch and one capacitive branch, and each branch drives a load which is made up of high-voltage LEDs. Percent flicker, power factor, and power efficiency are selected as three metrics, and their benchmarks are set to evaluate the performance of this circuit. Phase shift between the two branches is selected as a factor that can determine the circuit performance. The variations of percent flicker, power factor, and power efficiency as a function of phase shift are identified by theoretical analysis and are verified by experiments. The experimental results show that an optimal solution can be achieved for this circuit design at proper phase shift, where the benchmarks of the three metrics are reached.

8835-24, Session 6

Luminescence properties of rare earth ions doped glasses excited by broadband lights

Linjiao Ren, Xiaohua Lei, Chongqing Univ. (China); Weimin Chen, Chongqing Univ (China); Xiaoqing Du, Lei Jin, Yong'an Feng, Chongqing Univ. (China)

White LED occupies an important position in solid state lighting area. Compared with commercial white LED, the UV chip-pumped white LED including RGB-emitting luminescent glass performs better color index, thermal stability and so on. In the existing researches, the excitations of rare earth ions (REI) doped luminescent glasses are light source of fluorescence spectrophotometer, which can emit monochromatic lights. But when the glasses were used for white LEDs, the excitation light source is an ultraviolet chip with an emission bandwidth of about 5nm. So the luminescence properties of rare earth ions doped glass excited by broadband lights should be investigated.

Rare earth ions generally have plenty of well-shielded 4f states that can be excited by narrow peaks, such as Tb^{3+} and Eu^{3+}, so the change of excitation wavelength can greatly influence the intensity ratio of blue, green and red emissions which can be reflected in the chromaticity coordinate and CCT. Applying Ce/Tb/Eu co-doped calcium borosilicate glasses as examples, a computational model was presented to simulate the emission spectra of luminescent glasses excited by broadband lights, based on the dependences of excitation wavelengths on emission spectra, chromaticity coordinates and CCTs. The results show that for the same CCTs, the center wavelengths of chips are different with the excitation wavelengths of fluorescence spectrophotometers, which provides guidance to the application of luminescent glasses.

8835-25, Session 6

Characterization of piezoelectric fields in InGaN quantum wells of GaN-based LEDs

Yi-Chin Lin, Cheng-Yi Liu, National Central Univ. (Taiwan)

The net electric field in the InGaN MQWs would greatly affect the lighting efficiency and the optical performance of the GaN-based LED. The built-

in field, polarization field, carrier screening field, and the applied electric field are known to be the major electrical fields in the InGaN multi-quantum wells (MQWs) of the GaN-based LEDs. Among the above four electrical fields, the polarization field is directly related to the epitaxial GaN/InGaN property and epitaxial processes. The polarization field in the InGaN wells includes spontaneous and piezoelectric polarization. The spontaneous polarization comes from the nature of InGaN epitaxial layer. On the contrary, the piezoelectric polarization is caused by both lattice mismatch (LM) and CTE mismatch (thermal stress; TM) between InGaN well layers and GaN barrier layers. In the past, many researchers reported that the magnitude of the LM-induced piezoelectric field is larger than the TM-induced piezoelectric field by one order.

In this talk, we measured the piezoelectric field variation of the GaN-based LED chips die-attached on Cu substrates with different die-attachment processes. With the obtained piezoelectric field values, we found that the TM-induced piezoelectric field is dominant factor over the LM-induced piezoelectric field. The detail approach to define the piezoelectric field and decouple the piezoelectric field and screening field would be presented.

8835-26, Session 6

Monte Carlo simulation of radiation pattern for rare earth ions doped luminescent glasses under violet LED excitation

Xiaohua Lei, Yong'an Feng, Weimin Chen, Peng Zhang, Linjiao Ren, Xiaoqing Du, Chongqing Univ. (China)

Rare earth ions doped luminescence glasses are promising phosphor candidates in the fabrication of LEDs in the future due to their specific advantages, such as higher thermal stability, higher transparency, compared to current commercial LEDs. While radiation patterns of luminescent glasses are different from current commercial LEDs fabricated by phosphors, luminescent glasses play roles both in emitting light and adjusting light distribution. In order to investigate radiation pattern of luminescent glasses, luminescence physical model of flat glasses doped with single rare earth ion was presented. Process of photons acting on rare earth ions and transporting in the luminescent glasses, and output light distribution from luminescent glasses were simulated by Monte Carlo method based on violet LED. At last, the simulating of radiation pattern for luminescent glasses based on Monte Carlo method was proved by experiment.

8835-27, Session 6

Piezoelectric hysteresis effect on GaN-Based LED optical and electrical performance

Chao-Chi Chung, Cheng-Yi Liu, National Central Univ. (Taiwan)

GaN-based compounds are widely utilized in optoelectronic devices, such as light-emitting diode (LED), hetero-junction transistor, and laser diode. GaN-based compounds are piezoelectric materials because of their wurtzite structure. As a result, a piezoelectric field would be produced in GaN-based device structure, which would cause deterioration in the efficiency and carrier mobility of the devices. In this work, we found that the piezoelectric field induced in the GaN-based LED has a hysteresis behavior. The detail mechanism of the hysteresis behavior of the piezoelectric field in the GaN-based LED would be discussed in this talk.

Also, we found that the hysteresis effect in the piezoelectric field in the GaN-based LED would greatly affect the accuracy of the junction-temperature determination. Consequently, the thermal resistance defined by the junction temperature measurement would be a problem. In this talk, we will also discuss the calibration of the junction temperature measurement by considering the hysteresis effect in the piezoelectric field in the GaN-based LED.

8836-33, Session PMon

Optical-field induced volume- and surface-relief formation phenomenon in thin films of vitreous chalcogenide semiconductors

Ugis Gertners, Zanda Alute, Elina Potanina, Janis Teteris, Univ. of Latvia (Latvia)

The demand of lower cost surface-relief based optical instruments such as grating-based resonators or filters for waveguides, diffractometers, spectrometers, etc. is one of the main driving forces for the investigation of direct light-induced relief formation. The most common techniques for fabricating and investigating these surface-relief gratings involve an interferometric or holographic recording setup.

We have investigated that the light-induced mass transfer process strongly depends on the material itself and polarization of the light. The behavior of mass transfer and thus the resulting recording could be related to interaction between the polar photo-induced defects and the polarized electric field of recording beam. It has been shown that the mass transfer can be directed both ways – towards or away from the electric field intensity gradient. The evolution of surface relief in dependence from the recording time and polarization has been investigated in detail. The mechanism of the direct recording of surface relief on amorphous chalcogenide films based on the photo-induced plasticity has been discussed.

A direct recording technique is a comparatively new solution for lithography and, as shown in this report, provides new experimental techniques for better understanding of the interaction between the light and matter. The obtained gratings are very stable at room temperature, so this method can replace some of the chemical etching techniques and find a practical application in the applied physics.

8836-34, Session PMon

A conceptual design for a Cassegrain-mounted high-resolution optical spectrograph for large-aperture telescopes

Cynthia S. Froning, Steven Osterman, Univ. of Colorado at Boulder (United States); Eric Burgh, NASA Ames Research Ctr. (United States); Matthew Beasley, Planetary Resources, Inc. (United States); Paul Scowen, Arizona State Univ. (United States); Todd Veach, NASA Goddard Space Flight Ctr. (United States); Michael Lieber, Steven Jordan, Dennis Ebbets, James deCino, Ball Aerospace & Technologies Corp. (United States); Bruno Castilho, Cesar Oliveira, Lab. Nacional de Astrofísica (Brazil)

We present a conceptual design for a high resolution optical spectrograph appropriate for mounting at Cassegrain on a large aperture telescope. The design is based on our work on the Gemini High Resolution Optical Spectrograph (GHOS) project. Our design places the spectrograph at Cassegrain to maximize throughput and blue wavelength coverage, achieving R~40,000 resolving power over a simultaneous 320-1050 nm waveband with throughputs twice those of comparable instruments. The optical design use a two-arm, cross-dispersed echelle format with each arm optimized to maximize throughput. A fixed image slicer is used to minimize optics sizes. The principal challenge for the instrument is to minimize instrument flexure and degradation of the optical image. To ensure image stability, our opto-mechanical design combines a cost-effective, passively stable bench employing a honeycomb aluminum structure with active flexure control. The active flexure compensation consists of hexapod mounts for each focal plane with full 6-axis range of motion capability to correct for focus and beam displacement. We verified instrument performance using an integrated model that couples the optical and mechanical design to predict image performance. Our full end-to-end modeling of the system under gravitational, thermal, and vibrational perturbations shows that deflections of the optical beam at the focal plane are <29 µm per exposure under the worst case scenario (<10 µm for most orientations), with final correction to 5 µm or better using open-loop active correction to meet the stability requirement. Finally, we will discuss applications of our design and high fidelity modeling process to future instruments.

8836-35, Session PMon

Opto-mechanical analysis for 1-meter astronomical telescope

Kwijong Park, Jeong-Gyun Jang, Inwoo Han, Bi-Ho Jang, Dae-Hee Lee, Korea Astronomy and Space Science Institute (Korea, Republic of)

We developed the precise finite element model of an 1-meter telescope through auto or manual mesh generation. For gravity and temperature change, stress and displacement of the overall structure, and performance of mirror surface were analyzed.

8836-36, Session PMon

Radial in-plane electronic speckle pattern interferometry with divergent illumination

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Interferometry electronic speckle pattern (ESPI) is a very useful technique for deformation measurement of surfaces on mechanical elements. The illumination sources can be collimated or divergent, this last one, considering some approaches, adjustments and corrections in theoretical models in comparison with collimated illumination due the spherical wave front. The directions of deformation measurements is a function of the sensibility vector of the optical system used for this purpose, and are common measurements in orthogonal directions in the Cartesian coordinate system. In recent years a radial in-plane ESPI interferometer using conical mirrors, beam splitters and collimated illumination was proposed. The configuration of the optical system set up can be simplified considerably if we consider positioning a divergent illumination and a CCD camera near to the center of the optical axis. However, we must be very careful when considering these approaches in theoretical and mathematical models when performing measurements. The divergent illumination near to the analyzed surface carries an unacceptable error in measurements. In this paper, a radial-in-plane ESPI with divergent illumination and conical mirrors are analyzed for radial deformation measurements. The contribution of the sensibility vectors and an algorithm to correct errors due to the spherical wave front are presented too. Also, we show an example of strain hole-fields measurements in the radial direction around a crack tip in a plate when it is under tension loads.

8836-1, Session 1

The correct lens mount lightweighting and stress OPD analysis in Cassegrain telescope

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This article is discussing the correct lens assembly different mount barrels material in thermal cycle condition optical performance analysis. The system mass budget allocated to correct lens assembly was 5 Kg. Meanwhile, according with optical design the correct lens was made by fused silica, the lens diameter was 130 mm, and the mass was 2.3 Kg. Therefore, remain mass budget was 2.7 Kg; include the lens mount, spacer, mount barrel and retainer. The mount barrel material is made by invar. If the barrel materials are change to the titanium or aluminum, the mount barrel weight will decline 42% and 63% respectively. The surrounding temperature difference will affect mount barrels deformation, and cause lens deformation and stress Optical Path Difference (OPD). Thus, the off-axis ray path of the stress OPD calculation, must consider lens incidence point and emergence point. The correct lens deformation and stress in different thermal condition are solving by Finite Element Method (FEM) software. The stress calculation results can be weighting to each incidence ray path and calculate stress OPD. Meanwhile, the correct lens deformation on Z-direction can be fitted by rigid body motion and Zernike polynomial. The stress OPD and correct lens deformation fitting results can be used to evaluate the barrel material different, effect on correct lens assembly in telescope system.

8836-2, Session 1

The ASTRI SST-2M prototype: camera design

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The Cherenkov Telescope Array (CTA) is the next generation ground-based very high-energy (VHE) gamma-ray instrument that will explore our Universe above 10 GeV. The ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) “Flagship Project”, financed by the Italian Ministry of Education, University and Research (MIUR) and lead by the Italian National Institute of Astrophysics (INAF), is the Italian contribution to the CTA, supporting all activities related to the finalization of the CTA technological aspects. The main goal of the Project is the realization of a prototype Cherenkov Small-Size Telescope in double mirror configuration (ASTRI SST-2M) equipped with a detection Camera based on silicon devices of the SiPM type (made by HAMAMATSU). The technological solution adopted for the Camera is based on a focal plane detector consisting of a 37 SiPM sensors, to adapt the focal plane on a curved surface, as imposed by the optical design. Such a level of modularity is mandatory in order to fit as much as possible the required focal surface curvature. We provide in this paper an overview of the mechanical, thermal and electrical concept design of the Camera.

8836-3, Session 1

Design considerations in a novel fiber-coupled three degree-of-freedom displacement interferometer

Steven R. Gillmer, Jonathan D. Ellis, Univ. of Rochester (United States)

Heterodyne displacement interferometry is a widely accepted methodology capable of measuring displacements with sub-nanometer resolution. The objective of this research is to demonstrate a compact, fiber-delivered displacement measuring interferometer which can be used to simultaneously calibrate the linear motion and rotational errors of a translating stage using a single measurement beam. This novel interferometer utilizes differential wavefront sensing to measure target mirror displacement, and changes in pitch and yaw. Differential wavefront sensing uses a quadrant photodiode to measure four spatially separated interference signals within a single optical interference beam. Based on the geometry of the detector and the interference phase in each quadrant, the displacement and changes in target pitch and yaw can be measured.

The opto-mechanical design of a working prototype has yielded an instrument with a 90 mm x 100 mm x 50 mm (3.5 in. x 4 in. x 2 in.) footprint. Thermal deformations have been mitigated through the implementation of kinematic mounting. The Invar optical support structure of the interferometer is kinematically mounted to the stainless steel base to ensure that free expansion occurs away from a thermal datum which is coplanar to the reference mirror. As a result, the same thermal expansion is seen in the reference and measurement arms of the interferometer and thus cancel out. A linearized finite element stress analysis has been conducted on the Invar optical support structure in addition to the custom stainless steel squeeze clamps which house launch fiber collimators. Design considerations and preliminary testing of the working prototype will be presented.

8836-4, Session 1

Remote vibration sensor using fiber optic fused 2x2 coupler

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A simple fiber optic vibration sensor is designed using 2x2 multimode fiber optic coupler , based on the principle of reflection intensity modulation. An LED (650 nm) is used as source and high sensitivity photo-Darlington (PD) as detector to detect the modulated light intensity corresponding to the vibration of the object. A Simple detection circuit (to convert the modulated light intensity into its equivalent voltage signal and NI-DAQ with Lab VIEW software) is used to record the time domain signal (TDS) of the vibrator. By using Fast Fourier transform (FFT), the frequency and amplitude of vibrations are measured from TDS. The optical coupler with 80:20 splitting ratio is used in the design of sensor, that is made of multimode PMMA fiber with core/cladding diameters of about 980/1000 µm and is length of 100 cm. The light is coupled to the port A, will be split into (80:20) and part of the light is transmitted through the port C which act as a sensing probe and the other part is directed to PD1 through port D ,used as a reference probe. The light from port C is projects onto the vibrating object then the modulated reflected light is traced by the same port and directed to the PD2 through port B. The rational output of PD1 and PD2 avoids the effect of source signal power fluctuations and fiber bending loss. The calibrated 1mm linear region of the characteristic displacement curve is used to measure the amplitude of vibrations. High sensitivity vibration measurements are observed within the linear region of the characteristic displacement curve. The experimental results show that the sensor is capable of measure the frequency up to 3500 Hz with ~0.03µm resolution of vibration amplitude over a dynamic range of 0-1mm. The SNR (Signal to Noise Ratio) of the signal is also increased by the rational output with respect to the reference and sensing signals. In comparison with dual-fiber and bifurcated-bundle fiber, this sensor eliminates the dark region and front slope which facilitates the easy alignment. The simplicity of design, non-contact measurement, high degree of sensitivity, economical along with advantages of fiber optic sensors are attractive attributes of the designed sensor that lend support to real time monitoring and embedded applications.

8836-5, Session 1

Raytheon high-bandwidth large-angle and reactionless fast steering mirror

Islam Shawki, Raytheon Co. (United States); Andrew Bullard, Raytheon Space & Airborne Systems (United States)

Raytheon Space and Airborne Systems (SAS) has designed, built and tested a 3-inch diameter fast steering mirror (FSM) for space application. This 2-axis FSM operates over a large angle, has a very high servo bandwidth, has very low noise, and has microradian class line of sight accuracy. The FSM maintains excellent performance over large temperature ranges and has very high reliability with the help of fully redundant position sensors and actuator circuits. Additionally, the FSM is also reaction-compensated. The FSM has undergone extensive testing which include characterization of exported forces and torques and thermal vacuum testing.

8836-6, Session 2

Practical aspects of specification of extreme lightweight ZERODUR(R) mirrors for spaceborne missions *(Invited Paper)*

Tony Hull, The Univ. of New Mexico (United States) and SCHOTT North America, Inc. (United States); Thomas Westerhoff, Ralf Jedamzik, Antoine Lays, SCHOTT AG (Germany); Todd Jaeger, SCHOTT North America, Inc. (United States); John Pepi, L-3 Communications IOS-SSG (United States)

Attributes of Extreme Lightweight ZERODUR® Mirrors have been analyzed and described in our recent series of papers, and demonstrated in the form of Schott's representative 1.2m diameter mirror (88% isogrid lightweighted with f0>200Hz), which has been exhibited at the 2013 American Astronomical Society Winter Meeting, and SPIE's 2013 Photonic West. Not only are the attributes of this mirror material and mirror substrate design suitable for spaceflight, the manufacturing approach is compatible with attractive mirror substrate cost and delivery schedules. We will review recent data on the low magnitude and homogeneity of the coefficient of thermal expansion, and on the toughness of the material. This approach to mirror substrate design is compatible with mirror sizes from less than 0.5m to greater than 4m across. Round, hexagonal, elliptical and square mirrors are all compatible with this mirror approach. In this paper, we describe the basic substrate manufacturing approach, and discuss various trades available to the telescope architect. We will also list principal customer-specified parameters which are sufficient for Schott to provide design-for-manufacturability, optimized for either low cost or low mass. In this manner, the end user can efficiently obtain an optimized mirror without detailed knowledge of the manufacturing process.

8836-7, Session 2

Advanced composite materials for optomechanical systems

Carl H. Zweben, Zweben Consulting (United States)

The four classes of composites are now well established optomechanical system materials. They are: polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), and carbon matrix composites (CAMCs). The latter include carbon/carbon composites (CCCs). The success of composites has resulted in increasing use in consumer, industrial, scientific, and aerospace/defense optomechanical applications. They offer significant advantages over traditional materials including high stiffnesses and strengths, near-zero and tailorable coefficients of thermal expansion, tailorable thermal conductivities (from very low to much higher than copper), and low densities. Some manufacturing processes allow parts consolidation and reduce machining requirements. PMCs are the most widely used composites. Optomechanical applications date from the 1970s. For example, the High-Energy Astronomical Observatory (HEAO-2) spacecraft, launched in 1978, had an ultrahigh modulus carbon fiber-reinforced epoxy optical bench. Since then, both fibers and matrix materials have advanced significantly, and use of carbon fiber-reinforced polymers (CFRPs) has increased steadily. Space system examples include the Hubble Space Telescope, AXAF, UARS, James Webb Space Telescope and many others. Use has spread to many other airborne applications, such as the airborne SOFIA. Perhaps the most impressive CFRP applications are the fifty-four 12m and twelve 7m moveable ground-based ALMA antennas. The other three classes of composites have significant advantages over PMCs, including no moisture absorption/desorption or outgassing of organic compounds. CCC and CMC components have flown on a variety of spacecraft. MMCs have been used in space, aircraft and industrial applications. In this paper, we review key PMC, MMC, CAMC, and CMC optomechanical system materials, including properties, advantages, disadvantages, applications and future developments.

8836-8, Session 2

Design guidelines for high-dimensional stability of CFRP optical bench

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In carbon fiber reinforced plastic (CFRP) optomechanical structures, particularly when embodying reflective optics, angular stability is critical. Angular stability or warping stability is greatly affected by moisture absorption and thermal gradients. Unfortunately, it is impossible to achieve the perfect laminate and there will always be manufacturing errors in trying to reach a quasi-iso laminate. Some errors, such as those related to the angular position of each ply and the skin parallelism (for a bench) can be easily monitored in order to control the stability more adequately.

This paper presents warping experiments and finite-element analyses (FEA) obtained from typical optomechanical sandwich structures. Experiments were done using a thermal vacuum chamber cycling the structures from -40°C to 50°C. Moisture desorption tests were also performed for some specific configurations. The selected composite material for the study is the unidirectional prepreg from Tencate M55J/TC410. M55J is a high modulus fiber and TC410 is a new-generation cyanate ester designed for dimensionally stable optical benches. In the studied cases, the main contributors were found to be: the ply angular errors, laminate parallelism, fiber volume fraction tolerance and joints. Final results show that some tested configurations demonstrate good warping stability. FEA and measurements are in good agreement despite the fact that some defects or fabrication errors remain unpredictable. Design guidelines to maximize the warping stability by taking into account the main dimensional stability contributors, the bench geometry and the optical mount interface are then proposed.

8836-9, Session 2

On the strength of glass

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Glass has been ignored by most of the structural engineering community because of its brittle nature. Glass is an indispensable material in optical systems and sometimes safety, even human safety, depends upon optical glass elements that behave in a structurally reliable manner. One such occasion is to accommodate survey cameras in transport-class aircraft. Fortunately, glass has reliable structural properties and the methods for structural analysis and testing for glass have been well developed. Unfortunately, the glass suppliers have not chosen to publish the appropriate strength properties for many of their glasses. This paper describes the physics of the strength of glass and the engineering application of that physics to an airborne survey aircraft for the safety of its inhabitants.

8836-10, Session 3

Alignment and assembly strategies for AWARE-10 gigapixel-scale cameras

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Gigapixel cameras using lens arrays can contain hundreds to thousands of precisely positioned optical components and thus require fast, reliable methods for optical assembly and alignment verification. Our first one-gigapixel prototype camera (AWARE-2) and our four-gigapixel camera currently under development (AWARE-10) need active alignment and performance measurement procedures during assembly to ensure high quality images. Here we describe the methods that we have developed to ensure proper positioning of all optical components in the AWARE-10 system and the resulting optomechanical design decisions. AWARE cameras employ a single monocentric objective lens that is

shared by an array of smaller "micro-cameras", each composed of a set of smaller scale lenses. In AWARE-10, approximately two thousand pieces of individual optics must be aligned to a high level of accuracy in order to attain the desired optical resolution over four gigapixels. To guarantee proper alignment before final assembly, the objective lens and the micro-optics are checked separately. Using tools including autostigmatic microscopy, slanted edge MTF measurements, and flat field measurements, we can confirm the correct alignment of individual components before assembly. Optomechanical designs that incorporate the application of these alignment tools are described.

8836-11, Session 3

Development of a wide-field telescope

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A prototype of large wide field telescope is a Cassegrain telescope which covers 2° field of view with two hyperbolic mirrors, a 0.5 m primary mirror and a 0.2 m secondary mirror with multiple correction lenses. Optimization of telescope has been conducted with various opto-mechanical analyses under gravity, temperature and dynamic loads by using finite element analyses. Optical performance evaluation and image motion are also calculated based on line of sight sensitivity equations integrated in finite element models. Manufacturing of optical elements and structure and alignment, install and test observation of a wide field telescope will be discussed.

8836-12, Session 3

High-sensitive FBG pressure sensor using metal bellows

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A fiber-optic sensor scheme, capable of the simultaneous measurement of pressure and temperature using two in-line Fiber Bragg Gratings (FBGs) is reported. Sensor head is configured by embedding the two FBGs with metal bellows, such that FBG1 is sensitive to both pressure and temperature, whereas the FBG2 is only sensitive to temperature being shielded from external pressure. High pressure sensitivity is achieved due to lower spring rate in longitudinal direction to that of the large elastic modulus in transverse direction of the metal bellows. Pressure and temperature measurement is made by monitoring the shift of Bragg resonance wavelengths of the FBGs corresponds to variation in applied pressure and temperature. From the test results the obtained pressure and temperature sensitivities are 86 pm/psi and 9.1 pm/°C, over a dynamic range of 0-40 psi pressure, and 25-110°C temperature measurements respectively. The experimental results well agreed with the theoretical results and show good linearity. This simple design, economical and all fiber optic sensor can be used for liquid and gas pressure measurements, and under-water applications.

8836-13, Session 4

Optomechanical analysis of mirror mounting mechanism

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This paper is investigated to construct the self-developed fundamental capability which can apply to the opto-mechanical design and analysis in space telescope. The mounting mechanics is found to be a key issue to dramatically affect the optical performance in optical systems. Design and experiments are conducted to study the relationship between stress and wavefront error of the opto-mechanical systems by use of the interferometric measurement. Zernike polynomials and wavefront fitting is performed to study the mirror mounting mechanism. It is reported that mirror mounting stress will severely affect the wavefront errors of the optical system. Especially, the experimental results show that the unbalanced stress will increase the wavefront errors, especially in the terms of astigmatism and trefoil. In addition, the external transverse shear stress will also degrade the astigmatism aberration.

8836-14, Session 4

On the statistical distribution of optical parameters in manufactured systems

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Generating optical tolerances in software systems such as Code V or Zemax usually begins by modeling a perturbed optical system to capture the effect of simultaneous changes in lens radius, center thickness, and other critical parameters. The analyst would assume a statistical distribution of the relevant parameters for the Monte Carlo simulation. Unfortunately, the assumed distributions generally do not resemble the real distributions that occur in lens manufacturing. For example optical designers will typically assume that the distribution is symmetric about their chosen nominal value, but in many cases this assumption is predictably false. They might also assume that the distribution will be zero, or nearly zero, at the tolerance limits, and this, too, is often wrong. Obviously, the best option would be to have actual manufacturing data to inform our selection of a statistical distribution in a Monte Carlo simulation. Understanding these distributions will have other beneficial consequences. The designer (or manufacturer) could easily predict the cost of changing a particular tolerance (as a result of lost yield) for a given manufacturing process. The factors that influence these distributions are revealing. For example, short runs will have different distributions than long runs where the manufacturing process is mature. We will present manufacturing data and supporting analysis to help optical designers make more rational choices during the tolerancing process.

8836-15, Session 4

Next-generation lightweight mirror modeling software

William R. Arnold Sr., Jacobs Engineering Group Inc. (United States); Matthew Fitzgerald, Univ. of Illinois at Urbana-Champaign (United States); H. Philip Stahl, NASA Marshall Space Flight Ctr. (United States)

The advances in manufacturing techniques for lightweight mirrors, such as EXELSIS deep core low temperature fusion, Corning's continued improvements in the Frit bonding process and the ability to cast large complex designs, combined with water-jet and conventional diamond machining of glasses and ceramics has created the need for more efficient means of generating finite element models of these structures. Traditional methods of assembling 400,000 + element models can take weeks of effort, severely limiting the range of possible optimization variables. This paper will introduce model generation software developed under NASA sponsorship for the design of both terrestrial and space based mirrors. The software deals with any current mirror manufacturing technique, single substrates, multiple arrays of substrates, as well as the ability to merge submodels into a single large model. The modeler generates both mirror and suspension system elements, suspensions can be created either for each individual petal or the whole mirror. A typical model generation of 250,000 nodes and 450,000 elements only takes

5-10 minutes, much of that time being variable input time. The program can create input decks for ANSYS, ABAQUS and NASTRAN. An archive/retrieval system permits creation of complete trade studies, varying cell size, depth, and petal size, suspension geometry with the ability to recall a particular set of parameters and make small or large changes with ease.

The input decks created by the modeler are text files which can be modified by any editor, all the key shell thickness parameters are accessible and comments in deck identify which groups of elements are associated with these parameters. This again makes optimization easier. With ANSYS decks, the nodes representing support attachments are grouped into components; in ABAQUS these are SETS and in NASTRAN as GRIDPOINT SETS, this make integration of these models into large telescope or satellite models possible.

8836-16, Session 4

Thermal analysis of optical mount for cockpit display systems

Shravan Kumar, Vinod Karar, T. K. Jindal, Rakesh Kumar, Central Scientific Instruments Organisation (India)

This paper offers guidance to optomechanical designers on the safe mounting of glass lenses using elastomers. Elastomeric mounting isolates the lenses from strains, deflection, decentration and minimizes the thermal stresses build up with in the opto-mechanical components that is caused by differential radial expansion or contraction of the lenses, cell & elastomer under temperature changes. In this study various types of glasses being used for lens are SK14, SK15 and SF56A and Aluminium alloy 6061 for mechanical components like spacers, clamp, cell etc. The thermal loads being applied are of four types i.e. high temp storage cum operation(35 degrees C to 90 degrees C), low temp. storage(-55 degrees C), low temp. operating (-40 degrees C)and thermal shock(+70 degrees C to -40 degrees C). During FEA analysis, a model of the structure is created with three dimensional continuum of small elements and the elements being used in this study are tetrahedral elements. The modeling of the lens mount is performed by using solid works design tool and detailed finite element analysis (FEA) is performed by using COSMOS. The annular thickness of elastomer is optimized for minimum thermal stresses. The thermal stresses developed are very low and which are not affecting the optical performance of the system. It is witnessed that the analysis results and actual thermal test results are almost matching. The lens mounts designed and developed were qualified the thermal tests and are being used in cockpit display systems. Hence the results of the this paper are helpful to opto-mechanical designers for building up of stress free lens mounts required for cockpit display systems applications.

8836-17, Session 4

Integration of mirror design with suspension system using NASA's new mirror modeling software

William R. Arnold Sr., Jacobs Engineering Group Inc. (United States); Ryan M. Bevan, NASA Marshall Space Flight Ctr. (United States)

Advances in mirror fabrication is making very large space based telescopes possible. In the many applications, only monolithic mirrors meet the performance requirements. The existing and near-term planned heavy launch vehicles place a premium on lowest possible mass. Again, available and planned payload shroud size limits near term designs to 4 meter class mirror. Practical 8 meter and beyond designs could encourage planners to include larger shrouds if it can be proven that such mirrors can be manufactured. These two factors lower mass and larger mirrors, presents the classic optimization problem. There is a practical upper limit to how large a mirror can be supported by a purely kinematic mount system and be launched. This paper shows how the design of the suspension system and mirror blank needs to be designed simultaneously. We will also explore the concepts of auxiliary support systems, which act only during launch and disengage on orbit. We will define required characteristics of these systems and show how they can substantially reduce the mirror mass.

The AMTD project is developing and maturing the processes for future replacements for HUBBLE, creating the design tools, validating the methods and techniques necessary to manufacture, test and launch extremely large optical missions.

This paper will use the AMTD 4 meter "design point" as an illustration of the typical use of the modeler in generating the multiple models of mirror and suspension systems used during the conceptual design phase of most projects. The influence of Hexapod geometry, mirror depth, cell size and construction techniques (Exelsis Deep Core Low Temperature Fusion © versus Corning Frit Bonded © versus Schott Pocket Milled Zerodur © in this particular study) are being evaluated. Due to space and time consideration we will only be able to present snippets of the study in this paper.

8836-18, Session 4

Line-of-sight stabilization by inertial reaction

Allie M. Baker, Goodrich ISR Systems (United States)

A new concept for stabilization of a line-of-sight through the use of the reaction between two intertial members is introduced. This concept includes a mechanical kernel that will provide an immediate real-time correction for platform rotational movement about a single axis. This theoretical approach uses the Euler-Lagrange dynamics equations for its derivation as a problem in classical mechanics.

8836-19, Session 5

Design and analysis of isostatic mounts on a spaceborne lightweight primary mirror

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The paper is aimed at obtaining the optimum isostatic mount configuration for a ZERODUR® primary mirror with a pre-designed lightweight configuration on the back for a space Cassegrain telescope. The finite element analysis and Zernike polynomial fitting based on the Taguchi method are applied to the whole optimization process. Under the integrated optomechanical analysis, three isostatic mounts are bonded to the center of gravity of the mirror. Geometrical control factors and levels have been selected to minimize the optical aberrations under self-weight loading. Therefore, the primary reflective mirror has been assembled with isostatic mounts of various geometry and different rigid design. The optimum isostatic mount with the least induced astigmatism value is finally attained under the Taguchi method.

8836-20, Session 5

Flexure-mounted spaceflight laser for high g-load launch environment

Viatcheslav Litvinovitch, Joel Edelman, Fibertek, Inc. (United States)

Launching a precision optical instrument, such as a laser, into space presents a challenge due to the harsh structural and acoustic coupled loads that result from the launch vehicle engines. Special precautions must be implemented to protect the payload and attenuate the high frequency random vibration environment while still maintaining accurate alignment and beam pointing. Fibertek has designed, analyzed, and

tested novel Ti6Al4V flexures for isolating a space laser from a high g-load random vibration launch environment. Detailed finite element analysis was done to verify structural integrity of flight hardware by assessing the applied loads, load paths, and critical failure modes. Experimental data validated the modeling and the overall conclusions.

8836-21, Session 5

Optomechanical tolerancing and lens alignment using elastomeric lens mount to efficiently meet optical requirements

Frederic Lamontagne, Michel Doucet, Maxime Savard, Min Wang, INO (Canada)

Lens positioning accuracy and manufacturing cost are two main concerns for optomechanical engineers looking for solutions to reduce costs while meeting stringent optical and environmental requirements. Minimizing optical component positioning errors generally translates into significant cost increases. To maximize the precision-to-cost ratio, there are significant advantages in having both an accurate optomechanical tolerance calculation method and an effective technique to mount and align lenses.

This paper presents a tool that has been developed at INO to easily perform complex optomechanical statistical tolerancing using Monte Carlo simulation to reduce manufacturing and alignment costs. This tolerancing method provides a more realistic prediction of optical component errors compared to the classical worst case and root sum square calculations. In addition, precision alignment using elastomeric lens mounting is presented. Thermal stability and often overlooked factors for effective alignments are discussed. Results of tests performed on real optical assemblies are presented for tolerancing, thermal stability and alignment performance. The use of these methods can considerably reduce cost while efficiently ensuring compliance with requirements.

8836-22, Session 5

A unique mounting for miniature optics at cryogenic temperatures

Zachary N. Leahy, Andrew Magner, ITT Communications Systems (United States)

This paper highlights a mounting solution for miniature, high aspect ratio Zinc Selenide optics capable of sustaining high vibration loads and cryogenic temperatures. The GOES ABI Instrument optical design requires ZnSe filters that have a significantly higher than standard aspect ratio. The thin structure, along with the material properties of ZnSe lead to a filter that is very delicate. The mounting technique minimizes stresses induced over thermal extremes while maintaining sufficient preload for ambient launch loads.

The filters are mounted to metallic housings using a spring loaded retainer and compliant meterials. Detailed analysis of the mounting and an understanding of the unique material properties enables the design to be successful. Special attention is given to materials passing through glass transition temperatures.

This design was qualified through extensive thermal cycling and vibration testing and exhibited performance acceptable for production.

8836-23, Session 5

Optomechanical design of a modular K-B mirror mount system for x-ray microfocusing at the Advanced Photon Source

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The Kirkpatrick-Baez (K-B) mirrors are sophisticated x-ray micro- and nano-focusing tools for synchrotron radiation applications. A prototype of a modular x-ray K-B mirror mount system has been designed and tested at an optics testing beamline, 1-BM at the Advanced Photon Source (APS), Argonne National Laboratory (ANL). This compact, cost-effective modular mirror mount system is designed to meet challenging mechanical and optical specifications for producing high positioning resolution and stability for various scientific applications with focused hard x-ray beams down to 100-nanometer scale.

The optomechanical design of the modular x-ray K-B mirror mount system as well as the preliminary test results of its precision positioning performance are presented in this paper.

8836-24, Session 6

An athermal mounting of optics in metallic housings

Zachary N. Leahy, Andrew Magner, ITT Communications Systems (United States)

This paper illustrates a unique mounting for a Zinc Selenide optic in an AlBeMet housing for use at cryogenic temperatures. The GOES-R ABI instrument IR beamsplitter design successfully overcomes the significant delta in the coefficient of thermal expansion between the housing and the optic, and the brittle nature of the optic material. The high discrepancy in CTE is exacerbated by a large thermal range experienced between ambient assembly and cryogenic operation.

An athermal packaging of the optics and its bonded clips within a space constrained envelope controls stress over the wide temperature extremes. The opto-mechanical design is capable of maintaining optical alignment after exposure to high-G vibration inputs. Comprehensive testing qualified the design for production.

8836-25, Session 6

Design and measurement of bipod flexure mounts for the IRIS spectrometer

Isaac Weingrod, Catherine Chou, Obert F. Lindstrom, Frank P. Lopez, Howard C. Holmes, Craig L. Hom, J. Wes Irwin, David M. Stubbs, Jean-Pierre Wüelser, Lockheed Martin Space Systems Co. (United States)

The Interface Region Imaging Spectrograph (IRIS) is a NASA SMall EXplorer mission scheduled for launch in 2013. The spacecraft was designed and built at the Lockheed Martin Space Systems Company (LMSSC) in Sunnyvale, CA while the instrument was provided by the LMSSC Advanced Technology Center in Palo Alto, CA. The primary mission goal is to learn how the solar atmosphere is energized. IRIS will obtain UV spectra and images with high resolution in space (0.4 arcsec) and time (1s), focusing on the chromosphere and transition region of our sun, which is a complex interface region between the photosphere and corona. The IRIS instrument uses a Cassegrain telescope to feed a dual spectrograph and slit-jaw imager, which operate in the 133-141 nm and 278-283 nm range.

Within the spectrograph, there are sixteen optics, each requiring subtle mounting features to meet an exacting 5 nm RMS surface figure requirement. This paper covers the entire optomechanical design process for the most challenging optic mounts which include the Collimator, UV Fold Mirrors, and UV Gratings. Although all mounts are unique in size and shape, the fundamental design remains the same. The mounts

are highly kinematic, thermally matched, and independent of friction. Their development will be described in detail, starting with the driving requirements and an explanation of the underlying design philosophy. Next, the key design features and critical analyses are presented, finishing with a review of the test results.

8836-26, Session 6

Development of rotating prism mechanism and athermalized prism mounting for space

Chip R. Beebe, Mark J. Brooks, Michael W. Davis, Robert A. Klar, John M. Roberts, Peter W. A. Roming, Randall J. Rose, Gregory S. Winters, Southwest Research Institute (United States)

Space and launch environments demand robust, low mass, and thermally insensitive mechanisms and optical mount designs. The rotating prism mechanism (RPM), a component of the stabilized dispersive focal plane system (SDFPS), is a spectral disperser mechanism that enables the SDFPS to deliver spectroscopic or direct imaging functionality using only a single optical path. The RPM is a redundant, vacuum-compatible, self-indexing, motorized mechanism that provides robust, athermalized prism mounting for two sets of matching prisms. Each set is composed of a BK7 and a CaF2 prism, both 70 mm in diameter. With the prism sets separated by 1 mm, the RPM rotates the two sets relative to one another over a 180° range, and maintains their alignment over a wide temperature range (190–308°K). The RPM design incorporates self-indexing and backlash prevention features as well as redundant motors, bearings, and gear trains. The RPM was functionally tested in a thermal vacuum chamber at 210°K and <1.0x10-5 Torr, and employed in the top-level SDFPS system testing. This paper presents the mechanical design, analysis, alignment measurements, and test results from the prototype RPM development effort.

8836-27, Session 7

Test-validated alignment and stability performance of the JMAPS program focal plane array assembly in a cryogenic vacuum environment

Brian Thompson, Pedro Sevilla, Michael Watson, Trent Newswander, Duane Miles, James Peterson, Space Dynamics Lab. (United States)

Focal Plane Arrays (FPA) consisting of multiple Sensor Chip Assemblies (SCA) in a precision aligned mosaic are being increasingly used in optical instruments requiring large format detectors. The Joint Milli-Arcsecond Pathfinder Survey Mission (JMAPS) requires very precise positional alignment and stability of its 2 x 2 SCA mosaic at operational temperatures in order to meet its precision sky mapping mission requirements. Key performance requirements include: detector active area co-planarity, in-plane alignment and thermal stability. This paper presents an overview of the JMAPS Focal Plane Array Assembly, its alignment and thermal-mechanical stability requirements and associated test-validated performance in a cryogenic vacuum environment.

8836-29, Session 7

Implementing stray-light baffles for improved JWST NIRCam performance

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The Near Infrared Camera (NIRCam) instrument for NASA's James Webb Space Telescope (JWST) has an optical prescription which terminates at two focal plane arrays for each module. The instrument will operate at 37K after experiencing launch loads at ~293K and the focal plane array housings, including stray light baffles must accommodate all associated thermal and mechanical stresses. In addition, the stray light baffles must be installed in situ on the previously assembled flight modules. The main purpose of the FPAH stray light baffles are to effectively attenuate mission limiting stray light on the FPAs. This paper will provide an overview of the stray light baffle design, mechanical and optical analysis, implementation and test results.

8836-30, Session 7

Optomechanical analysis and testing of a fast-steering secondary mirror prototype for the Giant Magellan Telescope

Andrew C. Corredor, The Univ. of Arizona (United States); Won-Hyun Park, College of Optical Sciences, The Univ. of Arizona (United States); Myung K. Cho, National Optical Astronomy Observatory (United States); Young-Soo Kim, Korea Astronomy and Space Science Institute (Korea, Republic of)

The Giant Magellan Telescope (GMT) will be one of the next class of extremely large segmented mirror telescopes. The GMT will utilize two Gregorian secondary mirrors, and Adaptive Secondary mirror (ASM) and a Fast-steering secondary mirror (FSM). The FSM consists of six off-axis mirrors surrounding a central on-axis circular segment. The segments are 1.1 m in diameter and conjugated 1:1 to the seven 8.4 m segments of the primary. A prototype of the FSM mirror (FSMP) has been developed, analyzed and tested in order to demonstrate the mechanical and optical responses of the mirror assembly when subjected to structural and thermal loadings.

In this paper, the mechanical and thermal performances of the FSMP were evaluated by performing finite element analyses (FEA) in NX Nastran. The deformation of the mirror's lateral flexure was measured when the FSMP was axially loaded and the temperature response of the mirror assembly was measured when exposed to a sample thermal environment. In order to validate the mirror/lateral flexure design concept, the mechanical, optical and thermal measurements obtained from the tests conducted on mirrors having two different lateral flexures were compared to the responses calculated by FEA.

8836-31, Session 7

Development of the fast-steering secondary mirror for the Giant Magellan Telescope

Myung K. Cho, National Optical Astronomy Observatory (United States); Andrew Corredor, The Univ. of Arizona (United States); Won-Hyun Park, College of Optical Sciences, The Univ. of Arizona (United States); Michael Sheehan, Matt Johns, Jonathan Kern, Charlie Hull, Giant Magellan Telescope Project (United States); Eric Hansen, National Solar Observatory (United States); Young-Soo Kim, Korea Astronomy and Space Science Institute (Korea, Republic of); Seongdo Kim, Kyungsung Univ. (Korea, Republic of)

The Giant Magellan Telescope (GMT) Fast-steering secondary mirror (FSM) is one of the GMT two Gregorian secondary mirrors. The FSM is 3.2 m in diameter and built as seven 1.1 m diameter circular segments. The conceiving philosophy used on the design of the FSM segment mirror is to minimize development and fabrication risks ensuring a set of secondary mirrors are available on schedule for telescope commissioning and early operations in a seeing limited mode, thereby mitigating risks associated with fabrication of the Adaptive secondary mirrors (ASM). This approach uses legacy design features from the Magellan Telescope secondary mirrors to reduce risk. The final design of the substrate and support system configuration was optimized using finite element analyses and optical performance analyses. The optical performance predictions of the FSM are based on a substrate with a diameter of 1.058m (on-axis), 1.048m (off-axis), a depth of 120mm, and a face plate thickness of 20mm leading to a mass of approximately 90kg. The optical surface deformations, image qualities, and structure functions for the axial and lateral gravity print-through cases, thermal gradient effects, and dynamic performances were evaluated. The results indicated that the GMT FSM mirror and its support system will favorably meet the optical performance goals for residual surface error and the FSM surface figure accuracy requirement defined by encircled energy in the focal plane. The mirror cell assembly analysis indicated an excellent dynamic stiffness which will support the goal of 20 Hz tip-tilt motion.

8836-32, Session 7

Flexure design development for a fast-steering mirror

Won-Hyun Park, College of Optical Sciences, The Univ. of Arizona (United States); Andrew Corredor, The Univ. of Arizona (United States); Myung K. Cho, National Optical Astronomy Observatory (United States); Young-Soo Kim, Korea Astronomy and Space Science Institute (Korea, Republic of); Ho-Sang Kim, Kyoung-Don Lee, Institute for Advanced Engineering (Korea, Republic of)

Fast-steering mirror (FSM) is a key element in astronomical telescopes to provide real-time angular correction of line-of-sight error due to telescope jitter and wind-induced disturbance. The Giant Magellan Telescope (GMT) will utilize a FSM as secondary mirror under unfavorable wind condition that excites the telescope at the lowest resonance frequency around 8Hz. In FSM, there is a flexure in the center of the mirror that maintains it in place, namely constraining lateral displacements as a lateral support, while still allowing tip-tilt motion to steer. Proper designing of a central flexure is challenging to meet such a flexible specification and lateral loading capability as well as to minimize optical surface distortion forced by redundant constraints at the flexure. We have designed the lateral flexure and estimated its performance from variety of design case studies in a finite element analysis tool. Carefully designed finite element model in sub-system level including the flexure, lightweight mirror and 3 point axial supports allows whether the designed flexure being qualified within specifications. In addition, distorted surface map can be achieved as a function of forces that could be induced in telescope operation or due to mis-alignment errors during assembling. We have also built a test set-up to validate the finite element analysis results. Optical quality was measured by a phase shifting interferometer in various loading conditions and the measurements were decomposed by standard Zernike polynomials to concentrate specific surface shapes and to exclude low order shapes as measurement uncertainties.

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8837-1, Session 1

The market of huge monolithic mirror substrates for optical astronomy

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Professional astronomical telescopes are complex optical systems at the limit of technical feasibility. Often monolithic primary mirrors and sometimes even secondary mirrors with huge dimensions are used. Prominent examples are the two reflectors of the Large Binocular Telescope and the giant mirrors of the VLT, GEMINI, and SUBARU. The performance of such precision optical components significantly depends on the physical parameters and the quality of their substrate materials. Within this paper selection criteria for mirror substrates will be discussed, thereby considering the important technical parameters, but also commercial points and aspects of project management. Qualities and limitations of classical mirror substrate materials like Zerodur, ULE, Astrositall, borosilicate glass and Cervit will be discussed and compared to new substrate materials like silicon carbide and beryllium. The different suppliers and their production process will be presented. In addition large mirrors of existing observatories and of telescopes under construction will be listed, thereby concentrating on mirrors above three meter in diameter. An outlook on material trends and on future astronomical telescopes will close this overview on the market of huge monolithic mirror substrates for optical astronomy.

8837-2, Session 1

Large-silicon carbide optics for manufacturability

John W. Pepi, L-3 Communications IOS-SSG (United States)

For space-based use, projected needs are for large optics of the one-meter class that lie under 30 kg/m2 in mass areal density. Current space programs using glass optics, such as Kepler, exhibit a mass of 45 kg/m2, while JWST beryllium optics, including hardware attachment, are as low as 18 kg/m2.

Silicon carbide optics can be made lighter than glass, although not as light as beryllium; however, distinct advantages in thermal conductivity and expansion coefficient are evidenced at all temperatures, allowing for greater thermal flux , minimizing gradients and maximizing performance, both earth and space looking. For manufacturability and production, it is desirable to minimize weight while maintaining reasonable cell spacing for open back lightweight design, which will reduce both cost and risk.

To this end we perform a trade study to build such an optic that meets both mass and stiffness requirements while being within the regime of ease of manufacture. The design study chooses a hexagonal segment, 1.2 meters across flats (1.4 meters corner to corner), mimicking the JWST design. Polishing, mounting, test, and environmental operational errors are duly considered.

8837-33, Session PMon

Laser strength of dielectric interference coatings on optical materials, rods, and non-linear crystals

Vladimir V. Novopashin, Alexsandr V. Shestakov, POLYUS Research and Development Institute (Russian Federation)

The novel technologies and design in lasers and laser elements defined the new demands to optical coatings. The requirements for dielectric interference films include the increasing optical and physical properties. High performance dielectric interference coatings (anti-reflection, dielectric mirrors, polarizers, beam-splitters in broad spectral rage are observed. High resistance to laser radiation is one of the main efficiency parameter. For evaporation materials a traditional electron-beam evaporation method was used. Ion-beam assistance with active O2+ provided to obtain more density films, which are closed to their stoichiometry structure. This is urgent for high power lasers at 1064 nm, lasers in medium infrared region and also for disc lasers. These coatings were deposited on the surface of optical glass BK-7 or quartz, and on the surface of rods, passive Q-switches and nonlinear crystals (LiJO3, LiTaO3, KTP, BBO, LBO, KDP, DKDP). The effect of influence ion-beam at most extent revealed during evaporation oxide materials, where activated the mobility of atoms deposited on substrate. Pre-cleaning by the ion-beam of neutral gas (Ar+) before the evaporation was important when produce mirrors for Y3Al5O12 + Er3+ lasers to reduce the influence of water at 1800 – 3000 nm. Ion source use allowed to conduct the process of surface cleaning water soluble crystals KDP, DKDP, optical materials and crystals that are depended on air environment LBO, BBO, LiJO3. The improvement of optical properties evaporated films led to obtaining almost perfectly coatings and stabilized operating characteristics of lasers and laser elements.

8837-34, Session PMon

Measurements of density by using the emission-intensity ratio between ionic to atomic lines in a Nd:YAG LIBS indicate aluminum alloy (zeolites) fantastic properties

Osama M. Khalil, Cairo Univ. (Egypt)

Optical emission in LIPS is found to be an efficient method for determining material hardness by estimate the ratio between ionic lines and atomic lines for elements exist in the samples under test. We conclude in our work that the ratio between ionic lines and atomic lines gives indication about density not Hardness. The results indicate that aluminum alloy samplesunder compression have a higher hardness and low density. The comparison between the practical and the theoretical resultsindicate the effect of crater development and rim formation on thermal and mechanical couplingwhich affected the ablation rate of the laser beam.

8837-35, Session PMon

Vacuum-packaged infrared MEMS image sensor array

Jae Hong Park, National Nanofab Ctr. (Korea, Republic of)

Vacuum continues to be an enabling environment for electronic devices into the 21st century. Here, examples include infrared IR sensing systems. Outgassing from surfaces in these systems destroys these controlled ambients over time days to years. MEMS and MOEMS are not immune to these issues. Most of MEMS based sensors are sensitive to the operating pressure, the partial pressure of water vapor in the package, or both. For example, infrared sensors need to operate in a pressure 10-3 Torr in order to be thermally isolated from the outside world and maintain adequate sensitivity. The situation is further complicated by the need for high degrees of hermeticity leak rates on the order of 10-12 atm-cc/s and the lack of space to mount getters to control the contaminants in the package. Hermeticity is currently a significant issue in the microelectronics packaging field as a whole.

Hermetically packaging MEMS devices in a reliable and economical manner is a topic of great interest to the MEMS community. The development of MEMS technology has reached a point where the packaging of the device is proving to be more difficult than the actual device development itself. Many development groups are finding their efforts stymied at this point, and interest in MEMS packaging and related topics is at a high level. In this study, among various and significant factors such as structural and geometric design of a device, considering optical design, thermal design, electrical design, mechanical design, and process design, fabrication of the device, design and fabrication of a circuit, device analysis, property measurement, design and fabrication of optical system, and design and fabrication of package module on R&D for MEMS based opto-electro-thermo-mechanical device, we will address a methodology for design, fabrication, and analysis of MEMS based infrared sensor array packaging. Also, ultimate type of wafer level packaging will be introduced in a view point of design factors and structural differences compared with on-going metal packaging

8837-3, Session 2

Aluminum alloy 6061 and RSA-6061 heat treatment for large-mirror applications

Trent Newswander, Blake G. Crowther, Utah State Univ. Research Foundation (United States); Guido Gubbels, Roger Senden, RSP Technology (Netherlands)

Aluminum mirrors and telescopes can be built to perform well at a relatively low cost and short schedule if the material is processed correctly. However, the difficulty of making high quality aluminum telescopes increases as the size increases, starting with uniform heat treatment through the thickness of large mirror substrates. In this study, large aluminum blanks of both conventional 6061 per AMS-A-22771 and RSA-6061 were built, heat treated and stress relieved. Both blanks were destructively tested with a cut through the thickness. Hardness measurements and tensile tests were completed. The convential 6061 results showed good hardness throughout the part and good hardness uniformity. RSA-6061 hardness was less uniform and did not meet T6 specification in the center. Further testing of the RSA-6061 discovered important process modifications for successful T6 heat treating of the material. We present our results in this paper and make suggestions for modification of procedures and future work.

8837-4, Session 2

Design and manufacturing considerations for 0.25-1.5 meter beryllium telescopes for current and future space missions

Michael N. Sweeney, Mark R. Warren, Joseph Ho, Tom Vettese, Jeff Ruzan, Jeff Calvert, Don Douthit, General Dynamics-Global Imaging Technologies (United States)

Recently there has been resurging interest in beryllium telescopes ranging from 0.25-1.5 meter in aperture for various NASA space missions. The central design feature for each mission currently under consideration is an axially symmetric, all beryllium telescope.

Design considerations include achieving minimized mass simultaneous with demanding structural, thermal, and optical requirements on orbit after sustaining the rigors of space launch. Modern analysis tools and modeling techniques enable simulation of telescope wavefront errors resulting from environmental effects and the influences of bi-metallic bending. Manufacturing considerations include diamond point turning, coordinate measurement machine profilometry, computerized grinding and polishing, brazing of complex beryllium structures, very thin electroless nickel plating, and other advanced manufacturing technologies imperative to successful visible–NIR optical performance. Current design and manufacturing efforts on 0.60, 0.80, and 1.0 meter beryllium telescopes are profiled to illuminate the confluence of applicable design and manufacturing technologies.

8837-5, Session 2

Cost-effective aluminum beryllium mirrors for critical optical applications

Jack Duich, David Feikema, Inrad Optics (United States); Chris Huskamp, IBC Engineered Materials Corp. (United States); Raymond White, IBC Advanced Alloys (United States)

The unique performance of aluminum-beryllium frequently makes it an ideal material for manufacturing precision optical-grade metal mirrors. Traditional methods of manufacture utilize hot-pressed powder block in billet form which is subsequently machined to final dimensions. Complex component geometries such as lightweighted, non-plano mirrors require extensive tool path programming, fixturing, and CNC machining time and result in a high buy-to-fly ratio (the ratio of the mass of raw material purchased to the mass of the finished part.) This increases the cost of the mirror structure as a significant percentage of the procurement cost is consumed in the form of machining, tooling, and scrap material that do not add value to the final part. Inrad Optics, Inc. and IBC Advanced Alloys Corp. undertook a joint study to evaluate the suitability of investment-cast Beralcast(R) 191 and 363 aluminum-beryllium as a precision mirror substrate material. Net shape investment castings of the desired geometry minimizes machining to just cleanup stock, thereby reducing the recurring procurement cost while still maintaining performance. The thermal stability of two mirrors, (one each of Beralcast(R) 191 and Beralcast(R) 363), was characterized from -40F to +150F. A representative pocketed mirror was developed, including the creation of a relevant geometry and production of a cast component to validate the approach. Information from the demonstration unit was used as a basis for a comparative cost study of the representative mirror produced in Beralcast(R) and one machined from a billet of AlBeMet(R) 162 (AlBeMet(R) is a registered trademark of Materion Corporation). The technical and financial results of these studies will be discussed in detail.

8837-6, Session 2

The isotropic behavior of an anisotropic material: single crystal silicon (SCSi)

Douglas R. McCarter, McCarter Machine, Inc. (United States)

Single crystal silicon (SCSi), with its diamond cubic crystal structure, is completely isotropic in most properties important for stable optics. For example, thermal and optical properties are completely isotropic. The elastic and mechanical properties however are direction dependent. But we show that in spite of this, near-isotropic behavior can be achieved with component designs that utilize the maximum elastic modulus in directions with the highest loads.

The most significant anisotropic property of SCSi is the Young's modulus of elasticity. Literature values vary substantially around a value of 145 GPa. The truth is that the maximum value is 169 GPa in the <110> crystallographic direction, higher than that of many materials such as aluminum and invar. And since Poisson's ratio in this direction is an extremely low 0.064, distortion in the plane normal to the load is insignificant. While the minimum modulus is 130 GPa, a calculated average value, such as the Reuss average used for polycrystalline Si, is close to the maximum at approximately 160 GPa. So that he minimum modulus is almost irrelevant.

It is clear then that near-isotropic elastic behavior can be achieved in SCSi components in spite of anisotropic elastic properties when designs utilize this unique behavior. In this paper we will demonstrate sub-micron and sub-second response to loads placing SCSi as Pre-eminent in isotropic stability.

8837-7, Session 2

Design and manufacturing considerations for high-performance gimbals used for land, sea, air, and space

Michael N. Sweeney, Bryan L. Redd, Tom Vettese, David Uchida, General Dynamics-Global Imaging Technologies (United States)

High performance stabilized EO/IR surveillance and targeting systems are in demand for a wide variety of military, law enforcement, and commercial assets for land, sea, air, and space. Operating ranges, wavelengths, and angular resolution capabilities define the requirements for EO/IR optics and sensors, and line of sight stabilization. Many materials and design configurations are available for EO/IR pointing gimbals depending on trade-offs of size, weight, power, performance, and cost. Space and high performance military aircraft applications are often driven toward expensive but exceptionally performing beryllium and aluminum beryllium components. Commercial applications often rely on aluminum and composite materials.

Gimbal design considerations include achieving minimized mass and inertia simultaneous with demanding structural, thermal, optical, and scene stabilization requirements when operating in dynamic operational environments. Manufacturing considerations include precision lapping and honing of ball bearing interfaces, brazing, welding, and casting of complex aluminum and beryllium alloy structures, and molding of composite structures. Several notional and previously developed EO/IR gimbal platforms are profiled that exemplify applicable design and manufacturing technologies.

8837-8, Session 3

Optical test results of carbon composite mirrors from MISSE 7

Robert C. Romeo, Robert N. Martin, Composite Mirror Applications, Inc. (United States)

We report on the optical performance of carbon fiber reinforced polymer composite (CFRP) mirrors after 1 year exposure onboard the Materials International Space Station Experiment (MISSE 7). Mirror samples were placed on the MISSE 7 tray, outside the ISS from October 2009 and retrieved September 2011. The results from testing the returned flight samples show degradation in the mirror's aluminum coating. However, the surface figure of each mirror remained largely unchanged after 1 year duration on orbit. Test results will be compared against the original, pre-flight mirror tests for each of the 3 samples.

8837-10, Session 3

Thermal testing of a stacked core mirror for UV applications

Gary W. Matthews, Exelis Visual Information Solutions (United States); Charles S. Kirk, Steven P. Maffett, ITT Exelis (United States); H. Philip Stahl, NASA Marshall Space Flight Ctr. (United States); Calvin E. Abplanalp, Jet Propulsion Lab. (United States); Ron Eng, William R. Arnold Sr., NASA Marshall Space Flight Ctr. (United States)

The ASTRO2010 Decadal Survey stated that an advanced large-aperture ultraviolet, optical, near-infrared (UVOIR) telescope is required to enable the next generation of compelling astrophysics and exoplanet science; and, that present technology is not mature enough to affordably build and launch any potential UVOIR mission concept. Under Science and Technology funding, NASA's Marshall Space Flight Center and ITT Exelis have developed a more cost effective process to make 4m monolithic spaceflight UV quality, low areal density, thermally and dynamically stable primary mirrors. A proof of concept mirror was built and tested down to 250K which would allow imaging out to 2.5 microns. This mirror was thermally tested at the Marshall Spaceflight Center to understand the thermal changes between the processing temperature of 293K and the potential low end of the operational temperature of 250K. Isothermal testing results and front plate gradient results have been evaluated and compared to analysis predictions. Measurement of gravity effects on surface figure will be compared to analytical predictions. Future testing of a larger Pathfinder mirror will also be discussed.

8837-11, Session 3

Cryogenic optical performance of a lightweighted mirror assembly for future space astronomical telescopes: optical test results and thermal optical model *(Invited Paper)*

Ron Eng, William R. Arnold Sr., Markus A. Baker, NASA Marshall Space Flight Ctr. (United States); Ryan M. Bevan, NASA Marshall Space Flight Ctr. (United States) and The Univ. of Alabama in Huntsville (United States); James R. Carpenter, Michael R. Effinger, Darrell E. Gaddy, Brian K. Goode, Jeffrey R. Kegley, William D. Hogue, Richard D. Siler, W. Scott Smith, H. Philip Stahl, John M. Tucker, Ernest R. Wright, NASA Marshall Space Flight Ctr. (United States); Gregory L. Burdick, Craig D. Hanson, Charles S. Kirk, Steven P. Maffett, Gary W. Matthews, ITT Exelis (United States)

A 40 cm diameter mirror assembly was interferometrically tested at room temperature down to 250 degrees Kelvin for thermal deformation. The 2.5 m radius of curvature spherical mirror assembly was constructed by low temperature fusing three abrasive waterjet core sections between two face sheets. The 93% lightweighted Corning ULE mirror assembly represents the current state of the art for future UV, optical, near IR space telescopes. During the multiple thermal test cycles, test results of interferometric test, thermal IR images of the front face were recorded in order to validate thermal optical model.

8837-12, Panel Discussion

ESA initiatives to improve mechanical design and verification methods for ceramic structures *(Invited Paper)*

Graham Coe, European Space Research and Technology Ctr. (Netherlands)

No Abstract Available

8837-13, Panel Discussion

Influence of low-Earth orbit exposure on the mechanical properties of silicon carbide

David B. Witkin, The Aerospace Corp. (United States)

The influence of the Low-Earth orbit (LEO) environment on the mechanical strength of silicon carbide (SiC) was evaluated on two flight experiments as part of the Materials on the International Space Station Experiment (MISSE). SiC samples for modulus of rupture (MOR) and equibiaxial flexural strength (EFS) testing were flown on the Optical and Reflector Materials experiments (ORMatE) as part of MISSE-6 (launched on STS-123, March 2008; returned on STS-128, September 2009) and MISSE-7 (launched on STS-129, November 2009; returned on STS-134, June 2011). Two different SiC vendors provided material for each flight experiment. The goal of the experiments was to measure mechanical

properties of the flight samples and compare them to an equal number of similar samples in control and traveler sample sets. Complete characterization of the strength of brittle materials typically requires many more test specimens than could be reasonably accommodated on the ORMatE sample tray and statistical models based on few samples include large uncertainties. Understanding the results of the mechanical tests of MISSE samples required comparison to results from a statistically valid number of samples. Prior testing by The Aerospace Corporation of material supplied by the same four vendors was used to evaluate the MISSE results, including flight and control samples. The results showed that exposure to LEO over the durations covered by MISSE 6 and 7 (approximately 18 and 20 months, respectively) did not alter the mechanical strength of the silicon carbide for any of the vendors' materials.

8837-14, Session 4

Comparison of SiC mirror approaches

Keith Carrigan, Michael Riso, Shayna Khatri, Christopher Douglas, L-3 Communications IOS-SSG (United States)

Silicon Carbide (SiC) mirrors hold many advantages over traditional optical materials and are increasingly common in optical systems. The wide range of optical applications necessitates different approaches to the manufacturing and finishing of SiC mirrors. Three key advancements have led to this differentiation: 1) manufacturing of CVD clad SiC mirrors in near cost and schedule parity with Zerodur, 2) super-polish of amorphous Silicon claddings, 3) low-roughness polishing results of bare reaction-bonded SiC aspheres. Three approaches which utilize these advancements will be discussed, each with its own strengths and weaknesses for specific applications. The relative schedules and performance of these approaches will also be compared, with Zerodur used as a reference.

8837-15, Session 4

HoneySiC: a new optomechanical material for low-areal cost and density

William A. Goodman, Trex Enterprises Corp. (United States)

One of the major problems perceived for silicon carbide mirrors and structures is the cost associated with machining and lightweighting the material to the specifications of a drawing. Molded pedigrees of silicon carbide address these concerns by casting or molding a slurry and prefiring the slurry to make a consolidated and porous greenbody which is relatively soft and not very difficult to machine. The machined greenbody is then infiltrated with molten silicon in an exothermic process that yields a two phase reaction bonded silicon carbide material that must undergo a final machining step. Converted silicon carbide pedigrees machine a graphite or carbon/carbon precursor material to near net shape and then infiltrate the part with gaseous silicon monoxide or molten silicon to convert most or all of the carbon to silicon carbide. Some pedigrees are highly porous, while others may be dense of containing 2 or 3 different phases of material. We have created and demonstrated a new fiber reinforced silicon carbide material that combines the benefits of molding, infiltration and conversion processes. The resulting HoneySiC material requires a minimal amount of machining. HoneySiC material achieves lightweighting of 92% relative to bulk material and net production cost on the order of $38K per square meter (unpolished), less than half of NASA's goal of $100K per square meter.

8837-16, Session 4

State-of-the-art silicon carbide optical telescope assembly for the JMAPS mission

Daniel J. Catropa, L-3 Communications IOS SSG (United States)

L-3 Communications IOS-SSG (L-3 SSG) has recently completed development of an ultra low wavefront error and highly stable Silicon Carbide (SiC) optical payload for the Joint Milli-Arcsecond Pathfinder Survey (JMAPS) mission. Selection of SiC as the opto-mechanical material was driven by the JMAPS requirements for extremely low residual optical aberrations and distortion, and state-of-the-art temporal and thermal stability. JMAPS utilizes a passively athermalized design, combining SiC optics with aggressively lightweighted SiC metering structures. The resulting hardware has been optically tested over temperature, demonstrating an exceptionally low and stable system level wavefront error. This exceptional performance, combined with the aggressively lightweighted sinterbonded SiC structures developed, result in an instrument which represents the state-of-the-art from the perspective of optical performance and structural efficiency. We will provide an overview of the system, with emphasis on the SiC opto-mechanics, and system level test results.

Keywords: Silicon Carbide, JMAPS, Optical Testing, Space Sensors

8837-17, Session 4

Novel reactive chemical mechanical polishing technology for fabrication of SiC mirrors

Rajiv K. Singh, Arul C. Arjunan, Kannan Balasundaram, Purushottam Kumar, Sinmat, Inc. (United States)

Silicon carbide (SiC) is considered an excellent material for high performance optical applications because of its superior properties including extremely high specific stiffness (E/?), high thermal conductivity and excellent dimensional stability. However, silicon carbide is next only to diamond in hardness and is chemically inert. Both the precision machining required for shaping and the conventional finishing processes (lapping, polishing) of SiC mirrors is extremely slow making it expensive to produce a light weighted, super-polished SiC substrate. In addition, diamond which is typically employed to achieve reasonable polishing rate, creates sub-surface damage, high density of scratches and other polishing defects which leads to mid and high spatial frequency errors. This talk will focus on a novel reactive chemical mechanical polishing process for SiC mirrors which increases the removal rate by several folds over conventional process at the same time reduce the rms roughness to <0.5 nm. Challenges associated with polishing of polycrystalline SiC and multiple phase material e.g. grain delineation will be discussed. The effect of various components, chemical and mechanical, of the reactive polishing slurry on surface roughness will be discussed.

8837-18, Session 4

Manufacturing and optical testing of 800-mm lightweight all C/SiC optics

Masataka Naitoh, Tadashi Imai, Haruyoshi Katayama, Masahiro Suganuma, Yoshio Tange, Ryota Sato, Japan Aerospace Exploration Agency (Japan); Hidehiro Kaneda, Takuma Kokusho, Nagoya Univ. (Japan); Keigo Enya, Takao Nakagawa, Masaki Kotani, Kenta Maruyama, Japan Aerospace Exploration Agency (Japan)

We manufactured an 800mm diameter lightweight telescope that consists wholly of carbon-fiber reinforced silicon carbide (C/SiC) that is called HB-Cesic. All its parts, including optical bench and support structures, were made out of HB-Cesic. Owing to its high specific stiffness and high thermal stability, silicon carbide is becoming one of the outstanding materials applied especially to large, space-borne optics. Technologies of highly accurate optical measurement of such large telescopes on vacuum or cryogenic circumstances are also indispensable.

We tested the cryogenic deformation of the primary mirror mounted on an optical bench in a liquid-helium chamber. During the test, both the mirror and the optical bench were cooled to 18K. The deformation was 110nm RMS with no significant residual deformation after cooling, which

is very promising for the applicability of the C/SiC composite to large light weight cryogenic space optics.

In addition, we assembled the primary mirror into the 800mm telescope with a high order convex secondary mirror and tested its optical performances at the 6m diameter radiometer space chamber at Tsukuba Space Center in JAXA, where we prepared the interferometric metrological facilities to establish techniques to test large optical systems in a horizontal light-axis configuration.

We carried out the optical measurements of the 800mm telescope by stitching interferometry with sub-aperture array consisting of 300mm autocollimating flat mirror. We verified that our algorithm and simulations of the stitching method is to be applied to 3m-class aperture telescopes such as SPICA with an 1m-class optical flat as a sub-aperture.

8837-19, Session 4

Effect of grain size on microstructure, properties, and surface roughness of reaction bonded SiC ceramics

Michael Aghajanian, Craig Emmons, M Cubed Technologies, Inc. (United States); Steve P. Rummel, Paul Barber, II-VI Inc. (United States); Christopher T. Robb, Douglas L. Hibbard, Exotic Electro-Optics, Inc. (United States)

Silicon carbide (SiC) based ceramics have received significant study for optical applications due to high specific stiffness, high thermal conductivity and low coefficient of thermal expansion (CTE). Reaction bonded SiC ceramics, which are composites of SiC and Si, are of particular interest due to large size and complex shape capability. The behavior of these ceramics is very much affected by the respective volume fractions of SiC and Si, and the grain size of the SiC phase. The present work examines Si contents ranging from 10 to 35 vol. %, and SiC grain sizes ranging from 6 to 50 microns, with the goal of optimizing properties and finishing capability for optical uses. Microstructures are reviewed; physical, mechanical and thermal properties are presented; and post-polishing surface roughness data are provided.

8837-20, Session 5

Cryogenic silicon carbide mirrors for infrared astronomical telescopes: lessons learned from AKARI for SPICA *(Invited Paper)*

Takashi Onaka, The Univ. of Tokyo (Japan); Hidehiro Kaneda, Nagoya Univ. (Japan); Mitsunobu Kawada, Keigo Enya, Takao Nakagawa, Institute of Space and Astronautical Science (Japan)

Silicon carbide (SiC) has good thermal conductivity, high stiffness, and a relatively low specific density, all of which are advantageous to the application to telescopes operating at cryogenic temperatures. The first Japanese astronomical infrared space mission AKARI, which was launched in 2006 February and completed the second generation all-sky survey at 6 bands from mid- to far-infrared, employed a 700mm cryogenic telescope made of specially developed SiC. It was a sandwich-type of SiC composed of a lightweight porous core and a dense chemical vapor deposition (CVD) coat to decrease the specific density and facilitate machining without losing polishability to achieve the required wave-front errors. Optical tests at cryogenic temperatures (~10K) of 160-mm sample mirrors have demonstrated that the AKARI mirror SiC has a high stability at cryogenic temperatures, while the mirror support of the compact design became the primary source of wave-front errors of the telescope system. Taking the advantage of heritage of the AKARI telescope development as well as ESA's Herschel telescope, we are planning the next infrared space mission, SPICA (Space Infrared Telescope for Cosmology and Astrophysics) of a 3.2m cooled telescope in participation of ESA using SiC or carbon-fiber-reinforced SiC materials. In this presentation, we summarize the development of AKARI SiC telescope and present the development activities of the SPICA telescope from the point of view of SiC being as the material for cryogenic space telescopes.

8837-21, Session 5

Design and fabrication of ultralight and stable Cesic(R) mirrors

Matthias Krödel, ECM Engineered Ceramic Materials GmbH (Germany)

In the frame of a German R & D program ECM designed and fabricated an ultra stabile light weighted mirror to demonstrate the capability of Cesic® to manufacturing of such mirror structures especially for future large scale mirrors and structures. In this paper I will describe the design approach from a traditional open back mirror to the complex shaped super light weighted closed back mirrors in order to see the advantages of such mirrors compared to traditional mirrors.

Also I will report about the manufacturing of such complex shaped closed back mirrors which we developed during this R & D program.

8837-22, Session 5

Fabrication of SiC aspheric mirrors with low mid-spatial error

Flemming Tinker, Kai Xin, Aperture Optical Sciences Inc. (United States)

Manufacturing optics for today's most precise reflective imaging systems requires polishing techniques which enable extreme control over surface gradients and periodic features. This is critical for x-ray optics, which, are used at grazing incidence, high damage threshold laser optics, as well as applications in remote sensing, lithography and many other precision imaging applications. Most modern manufacturing techniques of fast aspheric optics produce mid and high spatial frequency features during grinding and polishing, which ultimately limit image quality. Mitigation of such features can be difficult, costly, and time consuming. Corrective finishing of such extreme optics must address and mitigate the impact of surface features corresponding to these various spatial scale lengths. This presents unique challenges to deterministic finishing techniques, which employ stable work functions and tool paths to surgically correct for surface errors. While such technologies and techniques may correct for errors in one spatial frequency region, they may inadvertently create new periodic errors, which can further degrade image performance. Manufacturing design must therefore address correction of the full measurable power spectrum to optimize image performance. This paper will discuss how controlled force grinding, robotic polishing, and surface smoothing can be employed to minimize and mitigate mid-spatial errors in fast silicon carbide aspheric mirrors. Recent experience and results are presented, which demonstrate how fabrication techniques that produce minimal surface gradients in the mid-spatial frequency region can produce superior image quality as predicted by the encircled energy or the point spread functions.

8837-23, Session 5

Correlation of mid-spatial features to image performance in aspheric mirrors

Flemming Tinker, Kai Xin, Aperture Optical Sciences Inc. (United States)

Modern techniques in deterministic finishing approaches employ geometrically small tools and removal functions for precision correction of fast aspheres. There are fundamentally sound and often necessary reasons for small tool finishing, however, a consequence is the creation of a residual trail of periodic surface "ripples" or textures in the surface

that can have profound impact on system imaging performance. There are many reasons for the creation of periodic features however, first order effects often result from the polishing tool or contact spot geometries. Creation of such features are inescapable. Therefore, it becomes necessary to better characterize them, understand their impact, and develop preventive, compensating and mitigating strategies of controlling their amplitudes and frequencies. Traditional specifications like Peak to Valley and RMS wavefront specifications cannot fully predict image quality in fast aspheric optics unless they are specified over precise spatial scale lengths (or frequencies). In this paper we will explore a variety of fast aspheric mirrors produced by Aperture Optical Sciences Inc. in the past year and will attempt to correlate mid-spatial frequency errors with typical metrics of predictive image quality such as the encircled energy function and the point spread function.

8837-24, Session 5

A sound basis for Snap-Together

Hugo Vargas, Poco Graphite, Inc. (United States); Flemming Tinker, Aperture Optical Sciences Inc. (United States)

The opto-mechanical performance advantages of silicon carbide (SiC) material are well understood and sought after for space and airborne applications. Furthermore, manufacturing technology maturity for making substrates and mirrors has evolved considerably over the past 10 years. What has been less known over this same period were the effects on improving and optimizing the fabrication process of a complete SiC assembly, that is, assembling and aligning mounting structures and mirrors. The performance of an athermal system is the 'holy grail' of design desires but if the challenges to achieving the optical assembly overwhelm the concept over traditional configurations (e.g., glass adhered to metal mounting structures), then a true technology advancement has not been attained. Entegris has manufactured several SiC optics and structures demonstrators under SBIR and BAA efforts, and now commercial deliverables, and has validated manufacturing pathways that clearly demonstrate advantages at many levels. This paper examines the details of fabricating a silicon carbide telescope leading to the assembly and alignment phase and the benefits within those phases directly attributed to Entegris' SUPERSiC material and manufacturing technology.

In 2012, Poco Graphite and Aperture Optical Sciences delivered a 6 inch on-axis two-mirror telescope demonstrator to the Air Force Research Laboratory as part of Poco's Broad Agency Announcement contract. The unique characteristics of the results attained after initial assembly will be discussed in this paper. Of particular interest are ease of assembly, first-light reading, and repeatability of the silicon carbide telescope. After precision machining and polishing of the individual silicon carbide structures and mirrors, optical metrology performed yielded a "first-light" reading slightly over 2 waves Peak-to-Valley. To understand repeatability characteristics, disassembled and re-assembled was performed multiple times and was timed 30 minutes total per cycle. The more impressive characteristic was that interferometer readings after each cycle yielded a maximum 0.2 waves Peak-to-Valley difference across the combined readings. This is a clear indication of the benefits of a highly stable material coupled with a superior manufacturing technology.

8837-25, Session 6

Development of CFRP mirrors for space telescopes

Shin Utsunomiya, Tomohiro Kamiya, Ryuzo Shimizu, Japan Aerospace Exploration Agency (Japan)

CFRP (Caron fiber reinforced plastics) have superior properties of high specific elasticity and low thermal expansion for satellite telescope structures. However, difficulties to achieve required surface accuracy and to ensure its stability in orbit have discouraged CFRP application as mirrors. We developed ultra-light weight and high-precision CFRP mirrors composed of CFRP skins and CFRP core sandwich structure using a replica technique.?The shape accuracy of demonstrated mirrors of 150 mm in diameter was 0.8 ?m RMS and the surface roughness was 5 nm RMS as fabricated. This improvement was achieved through observation of surface profiles at each phases of fabrication process of CFRP mirrors by using a surface profiler of scanning white-light interferometry. Technique to observe surface profiles as a function of observed dimension and measuring interval makes it possible to discern various causes of surface bumpy patterns. Optimization of process conditions improved surface accuracy of bare CFRP face skins to less than 1?m RMS. After sandwiched then replicated, surface accuracy of flat sandwich panels of 150 mm square was improved to 0.2 ?m RMS with surface roughness of 6 nm RMS. The surface accuracy vs. size of trial models indicated good possibility of fabrication of over 1m size mirrors of surface accuracy of 1?m. Stability of surface accuracy of CFRP mirrors against temperature and moisture will be presented elsewhere.

8837-26, Session 6

Composite tube manufacturing repeatability and performance as determined by precision measurements of thermal strain

Anthony M. Bluth, ATK Aerospace Structures (United States); Lenn A. Riddle, ATK Space Structures and Components (United States); James R. Tucker, ATK Space Systems (United States)

Composite materials often carry the reputation of demonstrating high variability in critical material properties. The JWST telescope metering structure is fabricated of several thousand separate composite piece parts. The stringent dimensional stability requirements on the metering structure require the CTE of every composite piece be verified either at the billet or piece part level. JWST is unique in that it has required the manufacturing of several hundred composite billets that cover many lots of prepreg and many years of fabrication. The thermal strain pass/fail criteria include limitations on thermal strain variation around a prescribed nominal when measured from 293 K down to 20 K and on the local thermal expansion rate between 30 K and 50 K. A precision measurement facility was developed that could measure at the required accuracy and at a pace that supported the composite part fabrication rate. The test method and facility is discussed and the results of a statistical process analysis of the flight composite billets are surveyed.

8837-27, Session 6

Prediction and measurement of composite tube twist and bending due to thermal loading

Anthony M. Bluth, ATK Aerospace Structures (United States); James R. Tucker, ATK Space Systems (United States); Lenn A. Riddle, ATK Space Structures and Components (United States)

Composite materials are applied in precision optical metering structures because of their low thermal expansion properties in concert high specific stiffness. Twisting and bending of long composite tubes, such as the secondary mirror support structure for the JWST telescope, requires control and verification. A stochastic modeling method was applied that simulates the manufacturing process variability and estimates ranges for expected twist and bend over the tube length from ambient to cryogenic temperatures. A development strut for the JWST secondary mirror support structure was fabricated and a metrology system was designed and implemented that measured the bend and twist response from ambient to 20 K. Modeling methods and predictions are outlined. The test metrology and results are summarized, along with a comparison between test and prediction.

8837-28, Session 7

Development of transparent polycrystalline beta-silicon carbide

Shyam S. Bayya, Guillermo R. Villalobos, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States); Michael P. Hunt, Univ. Research Foundation (United States); Bryan M. Sadowski, Ish D. Aggarwal, Sotera Defense Solutions, Inc. (United States); Michael K. Cinibulk, Air Force Research Lab. (United States); Carmen M. Carney, Kristin A. Keller, UES, Inc. (United States)

Transparent beta-SiC is of great interest because its high strength, low coefficient of thermal expansion, very high thermal conductivity, and cubic crystal structure give it a very high thermal shock resistance. A transparent, polycrystalline beta-SiC window will find applications in armor, hypersonic missiles, and thermal control for thin disc lasers. SiC is currently available as either small transparent vapor grown disks or larger opaque shapes. Neither of which are useful in window applications. We are developing sintering technology to enable transparent SiC ceramics. This involves developing procedures to make high purity powders and studying their densification behavior. We have been successful in demonstrating transparency in thin sections using Field Assisted Sintering Technology (FAST). This paper will discuss the reaction mechanisms in the formation of beta-SiC powder and its sintering behavior in producing transparent ceramics.

8837-29, Session 7

Novel high-performance polishing process for fabrication of sapphire window

Rajiv Singh, Kannan Balasundaram, Arul C. Arjunan, Purushottam Kumar, Sinmat, Inc. (United States)

Sapphire is highly transparent in the wavelength range 170 nm (UV) and 5.3 µm (IR) which makes it uniquely suitable for sensor window materials in electro-optical systems. Presently one of the outstanding challenges is the affordable, production of low-roughness, low-stress, large-area sapphire windows. Since, sapphire is among the hardest materials next only to few ultra-hard materials e.g. diamond, silicon carbide and also chemically inert, the polishing of sapphire is a challenge. The use of aggressive grinding technique provides relatively high removal rate of sapphire, however it leaves high degree of roughness, scratches and sub-surface damage which extends 2 to 5 microns below the surface. The final step of chemical mechanical polishing which uses slurries based on softer particles such as colloidal silica is a very slow process, and represents a major bottleneck. This talk will focus on a novel rapid chemical mechanical polishing process to increase the material removal rate during polishing of sapphire by greater than 2 fold over conventional process. A comparison will be made with the current state of the art process with respect to material removal rate, surface quality and window flatness. Polishing mechanism of sapphire and its correlation with process parameters e.g. particle, pad, pressure etc. will be discussed.

8837-30, Session 7

Silicate and direct bonding of low-thermal expansion materials

Gerhard Kalkowski, Simone Fabian, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Carolin Rothhardt, Friedrich Schiller Univ. (Germany); Mathias Rohde, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Paul Zeller, EADS Astrium GmbH (Germany); Stefan Risse, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We investigate materials adapted joining technologies for silicate glasses in high precision opto- mechanical applications using 150 mm diameter samples of ultra-low thermal expansion glass. Plane-spherical elements of exactly opposite radii and thicknesses of about 5 mm (massive) and 15 mm (perforated with bore holes), respectively, were first bonded at their spherical interfaces by a water based sodium silicate solution. Subsequently, the plane backside of the perforated part was closed with a glass wafer of 1.5 mm thickness by hydrophilic direct bonding to obtain a stiff, light-weight compound. Reliable bonds were achieved after extensive chemical cleaning and activation of the surfaces similar to previous practice /1/.

The dimensional stability of bonded compounds was tested in a vacuum chamber by monitoring flatness changes during thermal cycling. Gold coated plane surfaces of both sides were inspected at a resolution of 16 nm with a Fizeau type interferometer at temperatures between 330 K and 80 K. Probe mounting is displayed in Fig.2. Our contribution describes the bonding processes and documents the flatness changes of only about 30 nm RMS between both thermal extremes, illustrating the great potential of these technologies for application in space.

This work was supported by BMWI/DLR (Germany) under contract No. 50YB0814.

References:

/1/ G. Kalkowski, S. Risse, C. Rothhardt, M. Rohde, and R. Eberhardt, Optical contacting of low-expansion materials, Proc. of SPIE Vol. 8126 (2011) 81261F.

8837-31, Session 7

Recent developments in transparent spinel ceramic and composite windows

Shyam S. Bayya, Guillermo R. Villalobos, Woohong R. Kim, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States); Geoffrey D. Chin, Michael P. Hunt, Univ. Research Foundation (United States); Bryan M. Sadowski, Fritz Miklos, Ish D. Aggarwal, Sotera Defense Solutions, Inc. (United States)

The Naval Research Laboratory has pioneered the development of sintering processes for making highly transparent optical ceramics. For example, we have demonstrated the fabrication of record low absorption loss spinel as an exit window for High Energy Laser systems and rare earth doped Y2O3 and Lu2O3 for solid-state ceramic lasers. We have also developed thick spinel windows for submarine photonic masts and predicted the performance of an imaging system using testing and modeling. More recently, we have developed a novel approach of hot pressing where a transparent ceramic is produced in the net shape without requiring post polishing. This technology will result in significant cost savings associated with polishing the final optical element.

We had earlier identified a Barium GalloGermanate (BGG) glass with matching index and expansion coefficient to spinel. We had demonstrated fabrication of a laminated dome for the Joint Air to Ground Missile (JAGM) program and the technology was transitioned to industry. We have pushed this technology further by developing a BGG glass – spinel ceramic transparent micro-composite which can be processed well below sintering temperatures. To address the poor strength of BGG glass compared with spinel, we developed an ion-exchange process and achieved strengths up to 450 MPa. The results and status of all these development efforts will be discussed at the meeting.

8837-32, Session 7

Investigation of negative index in dispersive, chiral materials via contra-propagating velocities under second-order dispersion (GVD)

Monish R. Chatterjee, Tarig A. Algadey, Univ. of Dayton (United States)

Negative refractive index arises typically in metamaterials via multiple routes. One such avenue is the condition where the Poynting vector of the electromagnetic wave is in opposition to the group velocity in the material. An early work along this route in a chiral material led to the well-known result of requiring very large (non-realizable) chirality. Thereafter, a combination of chirality together with first-order dispersion was examined using plane wave electromagnetic analysis. To arrive at the conclusions in that approach, the three wave velocities (energy, group and phase) were derived under first-order dispersion in permittivity, permeability and chirality. Negative index in this approach was established under the condition of contra-propagating group and phase velocities. Regions of negative index were found analytically by assuming standard dispersive models (such as Condon). In this paper, we re-visit the negative index problem under higher-order dispersion. Accordingly, we re-examine the plane wave propagation model under parametric dispersion where each material parameter (ε, u, K) is dispersively expanded up to the second order in frequency. Such a physical effect may be traced to group velocity dispersion (GVD) in the material. Field solutions are then obtained under the GVD effect, and extended to the evaluation of the energy, phase and group velocities. Some well-known GVD models from the electromagnetic literature are then applied to the derived results for ve, vg and vp with dispersive coefficients, and conditions are established for the emergence of negative index. We further discuss the realizability of negative indices in practical GVD terms.

8838-1, Session 1

Angle and wavelength resolved light scattering

measurement of optical surfaces and thin films

Sven Schröder, David Unglaub, Alexander von Finck, Marcus Trost, Matthias Hauptvogel, Tobias Herffurth, Matthias Opel, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); John C. Stover, The Scatter Works Inc. (United States); Angela Duparré, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Light scattering metrology has become more and more important with the development of cutting-edge optical components and systems. Light scattering is also a very versatile tool for the characterization of nanostructures and defects. In the course of aiming for ever increasing resolution of optical devices and the need to analyze ever smaller structural features, the demands for highly resolved light scattering metrology have become extremely challenging. In this sense, “highly resolved” means: (i) measurements with high angular resolution, not just in one plane but within the entire scattering sphere, (ii) looking at optical, not just mechanical resolution, (iii) small near-angle limits, (iv) highest sensitivities close to or even below the Rayleigh scattering limit, and most recently (v) spectral resolution. Instruments for scatter measurements developed at Fraunhofer IOF to meet these demands are presented together with practical examples of application ranging from superpolished surfaces to thin film coatings. In addition to rather complex laboratory instruments, compact tools like a table-top 3D scatterometer and a CMOS-based scatter sensor are presented. Finally, we report on the development of a new instrument for spectroscopic angle resolved scatter measurements based on an OPO tunable laser.

8838-2, Session 1

Estimating hemispherical scatter from incident plane measurements of isotropic samples scattering from both bulk and surface irregularities

John C. Stover, The Scatter Works Inc. (United States); Sven Schröder, Alexander von Finck, David Unglaub, Angela Duparré, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

In the mid-1970’s it became apparent that incident plane scatter data could be represented by simple two or three parameter expressions. This realization made possible the generation of stray light estimation codes which are used on everything from military weapons, to telescopes, to car headlights to flat panel display systems. Almost all of these applications estimate hemispherical scatter from incident plane measurements. The author’s 2012 review of this process was limited to samples scattering just from surface roughness. In this paper hemispherical measurements are compared to calculations made from incident plane measurements using samples that scatter from bulk irregularities as well as surface scatter. The data is also analyzed to investigate reciprocity.

8838-3, Session 1

Calculating BTDF from window surface roughness

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The Rayleigh Rice vector perturbation theory has been successfully used for several decades to relate the surface power spectrum of optically smooth reflectors to the angular resolved scatter resulting from light sources of known wavelength, incident angle and polarization. A similar relationship should be available for the situation of a beam transmitting from a region of index greater than 1.0 into a region of unit index through an optically smooth surface. This paper presents such a relationship and compares the result to measured scatter data at two light wavelengths.

8838-4, Session 1

Use of the surface PSD and incident angle adjustments to investigate near specular scatter from smooth surfaces

Kashmira Tayabaly, Matthew B. Dubin, James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States); Robert E. Parks, Optical Perspectives Group, LLC (United States) and College of Optical Sciences, The Univ. of Arizona (United States); John C. Stover, The Scatter Works Inc. (United States)

The Rayleigh Rice vector perturbation theory has been successfully used for several decades to relate the surface power spectrum of optically smooth reflectors to the angular resolved scatter resulting from light sources of known wavelength, incident angle and polarization. While measuring low frequency roughness is relatively easy, the corresponding near specular scatter can be difficult to measure. This paper discusses using high incident angle near specular measurements along with profile generated surface power spectrums as a means of checking a near specular scatter requirement. Indeed, the specification in question, a BRDF of 1.0 sr-1 at 2 milli-radians from the specular direction and at a wavelength of 1 micrometer, is very difficult to meet by conventional scatter measurements. The sample under test being an uncoated Zerodur surface with relatively high bulk scatter, it was impossible to measure scatter directly. This paper presents profilometer and scatterometer data obtained from coated and uncoated flats at several wavelengths and outlines the analysis technique used to check this tight specification.

8838-5, Session 1

Sparse microdefect evaluation system for large fine optical surfaces based on dark-field microscopic scattering imaging

Yongying Yang, Dong Liu, Shitong Wang, Pin Cao, Xiaoyu Chen, Lu Li, Lu Yan, Zhongtao Cheng, Zhejiang Univ. (China)

It is considered challenging to evaluate the sparse microdefects of large optical surfaces because the microdefects are usually of microns while the test samples are of hundreds of millimeters. Most of the existing methods encounter problems such as uncertainty and inefficiency in eyeballing, inconsequence between laser source and international standard, limitation of detecting area, qualitative but not quantitative nor standard measurement of defects, etc. In this paper, a dark-field microscopic scattering imaging system for microdefects evaluation is introduced. The test sample, which can be of meter size, is illuminated by circular spaced white LED (Light Emitting Diode) light source. The scattering lights of the surface microdefects are captured by a digital microscope, thus the dark-field microscopic images of the microdefects are obtained. Since the test samples are usually of hundreds of millimeters or larger, the DM is controlled by an X-Y translation stage to collect sub-aperture images and sub-aperture stitching is employed to

obtain the full aperture image of the test sample. To obtain quantitative evaluation of the microdefects, a group of standard defects, such as scratches, pits, etc, are grooved by electron beam exposure and ion beam etching. As a result, the surface microdefects of the large aperture test samples can be resolved with submicron resolution. In this paper, the principle of the proposed surface microdefect evaluation system will be presented and the experiment results on evaluating numerous of test samples will be given. This system can also be employed for defect evaluation of small optical components, silicon chips and other applications that have high requirements for surface defects.

8838-6, Session 2

Measurement of a large deformable aspherical mirror using SCOTS (Software Configurable Optical Tests System)

Run Huang, Peng Su, College of Optical Sciences, The Univ. of Arizona (United States); Guido Brusa, Large Binocular Telescope Observatory (United States) and The Univ. of Arizona (United Kingdom); James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States)

SCOTS (software configurable optical test system), is an efficient metrology technology based on reflection deflectometry that uses only an LCD screen and a camera to measure surface slope. The surface slope is determined by triangulation knowing coordinates of the display screen, the camera and the test mirror. Some previous papers have reported the high performance of this technology in various applications, primary mirror of the Giant Magellan Telescope, refractive optics, high precision X-ray optics, etc.

In this paper, we present our recent SCOTS test results concentrated on high dynamic range measurements of low order aberrations. The varying astigmatism in the 91 cm diameter aspheric deformable secondary mirror for the Large Binocular Telescope was measured with SCOTS, requiring no null corrector. The SCOTS system was designed on axis with camera and screen aligned on the optical axis of the test mirror with the help of a 6 inch pellicle beam splitter. The on-axis design provided greater control of the astigmatism in the test. The high dynamic range of slope provided a measurement of astigmatism with 0.2 µm rms accuracy in the presence of 231 um PV aspheric departure. The simplicity of the test allowed the measurements to be performed at multiple elevation angles.

8838-7, Session 2

High-precision surface metrology of x-ray optics with an interferometric microscope

Ian Lacey, Nikolay A. Artemiev, Wayne R. McKinney, Valeriy V. Yashchuk, Lawrence Berkeley National Lab. (United States)

We describe a systematic procedure developed for surface characterization of super polished x-ray optical components with an interferometric microscope. In this case, obtaining trustworthy metrology data requires thorough accounting of the instrument's optical aberrations, its spatial resolution, and random noise. We analyze and cross compare two general experimental approaches to eliminate the aberration contribution. The reference surface approach relies on aberration evaluation with successive measurements of a high quality reference mirror. The so called super smooth measurement mode consists of subtracting two surface profiles measured over two statistically uncorrelated areas of the optics under test. The precisely measured instrument's modulation transfer function (MTF) and random noise spectrum allows us to correct the aberration-amended surface topography in the spatial frequency domain. An original MTF calibration method [Opt. Eng. 47(7), 073602 (2008)] is based on binary pseudo-random test samples specific for a particular arrangement of the microscope in use. While the developed measurement procedure is general and can be applied to various metrology instruments, the specific results presented are from a Zygo NewViewTM 7300 microscope.
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8838-8, Session 2

Non-contact metrology of aspheres and windows of large departure

Scott DeFisher, Edward M. Fess, OptiPro Systems (United States)

The measurement of large departure aspheres and windows is a challenge for the optics community. OptiPro systems has developed a non-contact measuring system called UltraSurf to overcome these difficulties. The UltraSurf system utilizes a single point non-contact sensor coupled with high accuracy air bearings to scan optical surfaces.

Five air bearing axes allow for the optical probe to maintain normal angles with the surface under test, and provide a smooth and accurate scan. The axes of motion allow scanning of rotationally symmetric parts such as spheres and aspheres, but also give it the freedom to perform areal surface scanning and freeform metrology. By maintaining a tangent angle with the surface, this technique allows for large surface slopes and deviation from best fit sphere to easily be measured.

Several commercial non-contact sensors have been integrated into UltraSurf. The sensors operate with different optical principles, allowing for greater flexibility of the types of surfaces to be measured. One sensor applies white-light confocal chromatic aberration for high resolution, single surface measurement. Another sensor that uses low-coherence interferometry with a 1310 nanometer light source is able to see through materials, enabling multiple surface and thickness measurements simultaneously.

Measurement of large departure aspheres and windows will be demonstrated. Cross comparison of UltraSurf data with current metrology techniques will be shown on surfaces that can be measured with multiple methods.

8838-20, Session 2

Analysis of three different measurement strategies carried out with the TII-3D coordinate measurement system

Florian Schneider, Hochschule Deggendorf (Germany)

Together with the group of interferometry based systems, coordinate measurement machines are an essential part of the metrology in the modern optical industry.

Coordinate measurement machines commonly consist of a multi axes framework. They are designed to operate in a defined three dimensional work zone, where every possible point can be reached by the measurement tool tip. This basic design principle leads to some interdependent challenges. A detailed measurement result needs a large amount of measurement points to detect even minor irregularities and short-wavelength errors. However, a rising of the amount of measurement points increases the corresponding measurement time analogous. On the other hand, the extended operation time increases the access of undesired thermal and dynamic influences, which cause multiple errors to the measurement result. Furthermore, modern production processes need rapid metrology systems to aid the machining time.

This paper discusses results obtained by operating with three different measurements in order to find an agreement between speed and certainty of the coordinate measurement machine. The topographic coordinate measurement system TII-3D had been re-developed at the University of Applied Sciences Deggendorf in the laboratory of optical Engineering and it is equipped with three different measurement strategies. The first mode, the Track Mode, operates in concentric circles on top of the surface of the object to be measured. The Spiral Mode measures along a dynamic moveable spiral line and the Sectional Mode

produces multiple cross-sections.

The results of this paper may be useful for the future design of measurement machines in general.

8838-10, Session 3

Algorithms for surface reconstruction from curvature data for freeform aspherics

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Increasing demand for highly accurate freeform aspheric surfaces requires accurate and efficient measurement techniques. One promising possibility uses a scanning system that measures curvature variations across the part. In this paper, we develop data processing algorithms that reconstruct the surface profiles from the curvature data. The performance of suggested methods and the sensitivity to noise is diagnosed.

8838-11, Session 3

Dynamic vibration-modulated sub-aperture stitching interferometry

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The sub-aperture testing methods have been widely used in the optical shop. It is developed to test the surface deformation of large diameter, high numerical aperture, or aspherical optical surfaces.

In this proposed research paper, we take advantage of the symmetry property of the axial symmetrical optical surfaces, and use four axis stages to measure the tested object that is optically nulled along the tangential direction. By adapting the vibration modulated phase shifting algorithm, the interferogram data is acquired on the fly without stopping the rotation motion of the tested lens during the measurement. The vibration modulated interference phase is then calculated and stitched into a global lens surface map in the least squares sense.

This method has advantages over the prior art in that it does provide the interferogram data in a much shorter acquisition time without extra hardware requirement. Thus, the interferometer can acquire hundreds of sub-aperture phase with very high resolution in a few minutes. The stitch error is then significantly decreased by increasing both the resolution of sub-aperture number and stitch overlap area.

8838-12, Session 3

Subaperture stitching performance estimation

Greg A. Smith, College of Optical Sciences, The Univ. of Arizona (United States); Chunyu Zhao, Univ. of Arizona (United States); Peng Su, James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States)

Subaperture stitching extends measurements such as interferometry by combining several overlapping measurements into a single, high-accuracy estimate of the overall image. In designing a subaperture measurement regimen, there are several tradeoffs related to size, quantity and locations of subapertures within the full aperture of the test optic. Understanding how individual subaperture measurement noise couples through these parameters into errors in the final stitched map is important for estimating overall system performance. In this work, we explore parametric rules for estimating the accuracy of stitched results based on subaperture geometry parameters and noise characteristics for a self-calibrating system where both a test optic and reference optic are simultaneously determined. From these rules, we examine types of errors introduced by stitching which enables confidence estimates for the final stitched map surface quality.

8838-13, Session 3

Calculation of the reference surface error by analysing a multiple set of sub-measurements

Roland Maurer, Hochschule Deggendorf (Germany)

The interferometry is probably the most important method of measurement in the field of precision optics. An interferometric measurement is always a relative measurement. The measured parameter is the optical path difference between the reference wave front and the test wave front. Since the surface quality of the reference lens can never be perfect, the interferogram is always a combination of the reference wave front error and the test wave front error. In the case of one single measurement which covers the whole test surface it is impossible to distinguish between these error-contributions. By using the stitching principle, one obtains multiple measurements at different positions on the test surface, whereas the reference wave front error is identical in each sub-measurement. As a consequence, the error contribution of the optical system may be estimated on the basis of the sub-measurements. Therefore two separated considerations are being done. First the contribution of each sub-measurement to the calculation of the real test surface error is determined. On the other hand the reference wave front error is also included in each sub-measurement. So in the second part the contribution of each sub-measurement to the calculation of the reference surface error is checked. This approach results in two over-determined linear equation systems, one for the determination of the test surface error and one for the calculation of the reference surface error. Each sub-measurement is taken into account with its Zernike-representation. The Zernike-coefficients for the estimated reference surface are calculated with the aid of a least squares fit. The results are compared with the results from the well-known metrology stage QED SSI-A from QED technologies.

8838-50, Session 3

Advanced surface metrology for meter-class optics

Martin J. Valente, Benjamin J. Lewis, Nicholas Melena, Mark A. Smith, Arizona Optical Systems, LLC (United States); James H. Burge, Arizona Optical Systems, LLC (United States) and Arizona Optical Metrology, LLC (United States); Chunyu Zhao, Arizona Optical Metrology, LLC (United States)

Refinements in computer controlled optical surfacing allow efficient grinding and polishing of meter-class optics to accuracy limited only by the surface metrology. We present a taxonomy of metrology methods and their implementation for meter class optical components. Interferometry with computer generated holograms provides nanometer accuracy for full surface measurements of a wide range of convex and concave aspheric surfaces. For measuring off-axis and freeform aspheric surfaces, the holograms include features that provide references for alignment. Very high spatial resolution is achieved with subaperture interferometric measurements which can be stitched together to provide a full-aperture map. Scanning systems complement the capabilities of interferometry by achieving larger dynamic range and providing independent corroboration. Optical coordinate measurement machines (CMMs) provide non-contact measurements of surfaces in their ground state to guide figuring, as well highly accurate measurements of finished optics. Scanning systems for measuring flat mirrors provide excellent resolution and absolute accuracy. The performance and practical issues for this full array of measurement techniques are presented to show the relative strengths of each method.

8838-16, Session 4

Metrology measurements for large-aperture VPH gratings

Jessica Zheng, Luke Gers, Jeroen Heijimans, Australian Astronomical Observatory (Australia)

The High Efficiency and Resolution Multi Element Spectrograph (HERMES) for the Australian Astronomical Observatory (AAO) use four large apertures, high angle of incidence volume phase holographic gratings (VPHG) for high resolution 'Galactic archaeology' spectroscopy. The VPH gratings work at an angle of incidence of 67.2º and line frequencies between 2400- 3800ln/mm. The large clear aperture, 525 mm x 200 mm, the diffraction efficiency, the line frequency homogeneity, and mosaic alignment made manufacturing and testing challenging. As a result ,a new metrology system was developed at the AAO to verify the performance of these VPH gratings.

There are two basic configurations for the new metrology system; diffraction efficiency and line frequency measurement. The diffraction efficiency setup is comprised of a goniometer, a stable white light source coupled to a 200 mm aperture off-axis collimator, and collecting optics coupled to a spectrum analyser. The line frequency metrology system has two different configurations each using the goniometer and high coherence laser. One configuration, a double pass system using a point source microscope (PSM) with a return flat and the other configuration using a 140mm diameter refracting telescope coupled to a CCD camera.

The measured VPH grating performances are in good agreement with vender's measurement results and they are close to the designed values.

8838-17, Session 4

Optical testing with computer generated holograms: comprehensive error analysis

Chunyu Zhao, James H. Burge, Arizona Optical Metrology LLC (United States)

Interferometry with computer generated holograms (CGHs) has become the industry standard for accurate measurements of aspheric surfaces. The CGH is a diffractive optical element that can be designed to create virtually any phase or amplitude distribution, and can be accurately manufactured using methods and equipment developed for integrated circuit production. Surface measurements with nanometer level precision can be performed using accurately well-calibrated equipment. This paper provides a systematic analysis of all significant sources of error for CGH metrology, including sources of pattern error, substrate irregularity and calibration, and system alignment.

Limitations in the design, fabrication and alignment of the CGH lead to errors in the interferometric measurements. In the design process, a CGH phase function is obtained which ideally produces null fringes in the measurement of an aspheric surface. Any deviation from null leads to error in the measurement. In the fabrication process, the first step is to encode the CGH phase function to pattern data that the writing machine recognizes. Then the pattern is written onto a substrate. For phase type CGH, additional steps are taken to etch patterns into the substrate. Each of these steps introduces error which could be estimated. In addition, the substrate the CGH pattern is made on introduces error as well. And the substrate can be calibrated, and the residual error can be estimated. In the final use of the CGH, any alignment error of the CGH introduces a wavefront error that degrades the measurement accuracy. The errors are described, quantified, and combined to provide a comprehensive assessment of the measurement accuracy.

8838-18, Session 4

Holographic radius test plates

Quandou Wang, Ulf Griesmann, National Institute of Standards and Technology (United States)

Radius and sphericity, the local departure of a near spherical surface from the best-fit sphere, together fully characterize a spherical surface. The sphericity of a spherical surface can be measured easily with a Fizeau interferometer that is equipped with a Fizeau objective, or transmission sphere. Measuring the radius of of a spherical surface is generally more difficult. If a measurement with low uncertianty is required, the radius bench method must be used. A part with a spherical surface is moved in an interferometer with spherical test wavefront along the optical axis from a position at which the test beam focus is at the part surface (cat's eye), to a position at which the test beam focus is at the center of curvature (confocal). The distance between these two positions is the part radius.

The lowest measurement uncertainty for the radius can be achieved when the distance is measured with a displacement measuring laser interferometer. The radius bench method is flexible and it can be used to measure radii of spherical surfaces in a wide range, at the expense of considerable complexity of the measurement setup.

For many applications this flexibility is not needed, because the radius of a surface is known approximately and only the departure of the radius from a nominal value must be determined. We describe a test method that uses a zone plate with two nested areas that is positioned in the test beam of a spherical Fizeau interferometer. The zone plate at the center of the nested zone plate generates a focus at the test part surface, whereas the -1st diffraction order of the outer zone plate is a wavefront that is confocal with the test part.

When the test part radius is the same as the nominal radius, the fringes in both areas are nulled at the same distance of the test part from the zone plate. The defocus term of a Zernike surface height map is calculated in both zone plate areas for several positions around the cat's eye position of the inner zone lens. The radius error of the spherical surface can be calculated from the defocus term in the confocal area at the position of zero defocus in the cat's eye area of the zone plate.

8838-19, Session 4

Wavefront retrieval for cross-grating lateral shearing interferometer based on differential Zernike polynomial fitting

Tong Ling, Dong Liu, Lei Sun, Zhongtao Cheng, Yongying Yang, Zhejiang Univ. (China)

In experiments of inertial confinement fusion (ICF), the thickness uniformity of capsule and the density uniformity of deuterium-tritium (DT) ice are both key to successful ignition, while the cross-grating lateral shearing interferometer (CGLSI), which is accurate and insensitive to disturbance, can be employed to test the density distribution of DT ice precisely. In this paper, a wavefront retrieval method for CGLSI based on differential Zernike polynomial fitting is presented. Fast Fourier transform technique is employed to get the frequency spectrum of the interferogram obtained by CGLSI. By performing inverse fast Fourier transform (IFFT) of the +1 order spectrum in both X and Y directions, it is possible to extract shearing wavefronts from the interferogram in both two orthogonal directions. Utilizing differential Zernike polynomial fitting method, we are capable of integrating two shearing wavefronts in X and Y directions together and retrieving the wavefront under testing. In the process of solving Zernike coefficients, the characteristics of differential Zernike orthogonal polynomials should be taken fully into account in mathematical modeling. To avoid the retrieval error introduced due to matrix mutation, the determination of discrete grid number and aperture shape must be in line with the theory that Zernike orthogonal polynomials are orthogonal over a unit circle as well. The result of simulation analysis shows that the wavefront retrieval method for CGLSI based on differential Zernike polynomial fitting is correct and accurate, and the root-mean-square error of this method is less than $\lambda/15$.

8838-38, Session PMon

Freeform surface-machining error-compensation method for ultra-precision slow tool servo diamond turning

Chun-Chieh Chen, Chien-Yao Huang, Wei-Jei Peng, Yuan-Chieh Cheng, Zong-Ru Yu, Wei-Yao Hsu, Instrument Technology Research Ctr. (Taiwan)

Recently, the optical freeform surface has been widely applied in optoelectrical industry, such as head-up display, astigmatism contact lens, progressive additional lens and f-theta lens for laser printer. To generate these freeform surfaces, ultra precision machining methods including Fast tool servo, slow tool servo, fly cutting and diamond milling methods are mainly used. Slow tool servo (STS) has the advantages of no extra attachment and fast setting-up in comparison with the other machining method. In the previous research, we have developed a model of three dimensional tool shape compensation for generating 3D tool path in slow tool servo diamond turning.

STS is one kind of facing operation, the cut-depth (Z-axis) is a function of radial (X-axis) position and work spindle angular position (C-axis). As the work-piece rotates, the diamond tool oscillates in and out of Z-axis motion to generate the required surface. Z-axis motion speed and accuracy are constrained by the frequency response of linear motor. When the more distance of Z-axis motion sets, the higher following error generated. Therefore, the form error increases with large surface sagitta and tangential slope. In this study, we presented a compensation method to improve the surface error. And the experiment result shows that surface form error has been compensated from 3μm to less than 1μm by the compensation method.

8838-39, Session PMon

FEM analysis of hot-pressing process of aspheric glass P-SK57 lens

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Lens molding has become the promising technique to conduct mass produce of aspheric glass lens. It overcomes some disadvantages of traditional grinding or turning methods, such as high cost, low efficiency, unstable accuracy, and so on. Up to now, the lens molding process has been looked on as one of the reliable methods in fabrication of aspheric glass lens. However, in real production, one has found that it's hard to control the molding parameters, e.g. molding temperature, molding period, molding speed and pressing pressure, etc. Therefore it's necessary to develop the specific molding processes for a certain glass material. In this paper, through FEM simulation, the lens molding process has been conducted as for glass of Schott P-SK57. Three stages of heating, pressing and annealing have been simulated separately to achieve the relative processing parameters. Based on three different pressing temperatures of 510°C, 520°C and 530°C, it's known that the heating duration is taken as 450s and the best pressing temperature is at 530°C. Meanwhile, the pressing velocity can be chosen as 0.1mm/s. After pressing at 530°C, the residual stress is only 5.22mpa. In filling ratio, it's only 96.07% at 510°C; 98.51% at 520°C and 99.02% at 530°C. It proves that the filling effect can meet the molding requirements at 530°C. Therefore, it's suggested that the best molding temperature could be taken as 530°C with pressing velocity of 0.1mm/s for low-melting P-SK57.

8838-40, Session PMon

New design of null screens to simplify the correspondence during the quantitative evaluation of optical surfaces

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We have been working in a method for testing fast aspheric convex surfaces with flat null screens in an array of LCD's, based on the null screen principles accordingly; i.e. We have demonstrated qualitatively that using three LCD's forming a triangular prism, we can evaluate aspheric fast surfaces instead of the traditional test of cylindrical null screen. This setup of LCD's has the advantage of display a series of 3 null screens for sampling an optical surface simultaneously, where in the ideal case, the position of the drop-shaped spots should be forming a regular square array of points in the image plane. However, due to typical problems of illumination and directionality with the transmitted light through the LCD's, some spots on the image are missing which complicates the correspondence between centroids and coordinates of the null screens, which is important for the quantitative evaluation in the numerical integration procedure used. In this paper we propose the design of null screens with reference marks, which provide unambiguous correspondence. Specific designs include some strategic color and position coding to ease the image spots identification. We show the method as used during the quantitative evaluation of a spherical steel ball.

8838-41, Session PMon

Development of a prototype of the GMT fast steering mirror

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Giant Magellan Telescope (GMT) Fast Steering Mirror (FSM) is a common secondary mirror comprised with seven segments. FSM has a fast focal ratio of 0.65 and is 3.2 m in total diameter whose segment is 1m in diameter. The surrounding six segments except the center one are off-axis mirrors. FSM also contains an implemented tip-tilt mechanism which compensates image degradations caused by wind disturbances and structure jitter.

Korea Astronomy and Space Science Institute is developing a prototype of the FSM together with collaborators in Korea and USA. The prototype is a full-size FSM segment, and it is divided into two features functionally; an off-axis mirror and a test-bed for tip-tilt actuation. The off-axis mirror with a diameter of 1.06m is being fabricated. Light-weighting of the mirror at the backside was performed first. Polishing of the front surface is finished and figuring is in progress. Several types of tip-tilt test-beds have been produced by integrating together with a dummy aluminum mirror, three axial supports, a lateral support, and various test-bed frames. Each component has been verified, and assembled test-beds are being verified. In this paper, we present the progress of the prototype development, and future works.

8838-42, Session PMon

The optical performance test of a lightweighting primary mirror of an aerospace Cassegrain telescope

Wei-Cheng Lin, Instrument Technology Research Ctr. (Taiwan)

The optical remote sensing instrument (RSI) of FORMOSAT-5 satellite is an aerospace cassegrain telescope with 450 mm diameter clear aperture. In order to meet both thermal and weight requirement, the primary mirror is using Zerodur and light weighted as the ratio about 50 %. For this mid-large lightweight mirror, the optical performance test is a modern technique whether in the manufacture or assembly process. While in the optical measurement, there are some inconsiderable measurement errors caused erroneous judgments for the mirror. It's difficult to specify the measured astigmatism caused from the form error after polishing or surface deformation by the external force from the supporter or mechanical mount. In this paper, the optical performance test called bench test with different supporter compared with vertical and horizontal setup is presented. After measurement, a novel algorithm to analyze the astigmatism caused from the gravity effect, form error from manufacture and the deformation from the mounting or supporter was presented.

8838-44, Session PMon

Practical absolute optical surface metrology and novel applications in adaptive optics

Eric E. Bloemhof, National Science Foundation (United States)

Practical application of a recently-devised absolute metrology scheme based on comparison of transversely-shifted frames from a commercial Fizeau interferometer (E. E. Bloemhof, Opt.Lett. 35, 2346, 2010) will typically require interleaving data sets with spatial frequency sampling incommensurate with the pixel spacing. These procedures are presented, and it is shown, somewhat counterintuitively, that no large degradation of spatial resolution results. While obviously useful in characterizing laboratory optics, where the new technique appears simpler and more sensitive than the classical 3-flat technique, there are also interesting applications in adaptive optics systems, such as diagnosing non-common-path errors. These and other applications are presented and analyzed.

8838-45, Session PMon

Incorporating skew into RMS surface roughness probability distributions

Mark T. Stahl, H. Philip Stahl, NASA Marshall Space Flight Ctr. (United States)

The standard treatment of RMS surface roughness data is the application of a Gaussian probability distribution. This handling of surface roughness ignores the skew present in the surface and overestimates the most probable RMS of the surface, the mode. Using experimental data we confirm the Gaussian distribution overestimates the mode and application of an asymmetric distribution provides a better fit. Implementing the proposed asymmetric distribution into the optical manufacturing process would reduce the polishing time required to meet surface roughness specifications.

8838-46, Session PMon

A study on the characteristics for ultra-precision machining technique using single-diamond turning machine

Wookang Kim, Geonhee Kim II, Geunman Ryu III, Meyeongsang Huh, Korea Basic Science Institute (Korea, Republic of)

In this paper, the cutting effect of Al-alloy using a single diamond turning machining is applied to make on aerospace spherical mirror. The ultra precision cutting has been done in the thermal vacuum chamber and the experimental tryout was minimized using the optimum processing conditions which were determined design of experiments. In this study, we considered three influenced factors on the surface roughness such as cutting speed, feed rate and depth of cut. The purpose of this research is to find the optimum machining conditions for cutting reflector apply the SPDTM technique to the manufacturing of ultra precision optical components of Al-alloy spherical reflector. The cutting force and surface roughness are measured according to each cutting conditions. We achieved the spherical mirror in the 300mm diameter with the surface roughness and the shape accuracy. We also show that the values can be applied to make the Al-alloy spherical reflector using diamond turning machine to perform cutting processing.

8838-47, Session PMon

Refractometer based on a double slit optofluidic interferometer. Prism refractometer.

Sergio Calixto-Carrera, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

Basic optofluidic elements are composed of spherical cavities, microchannels and other structures. Liquids can flow through the structures of these optofluidic elements. Here we propose a refractometer that consists of two hollow microchannels where fluids can be inserted. When light illuminates the double channel an interference pattern is shown in the far field. If a liquid with different refractive index is inserted in one microchannel the interference pattern presents a linear movement. It is possible to find a calibration curve relating the liquid refractive index as a function of the number of fringes that had passed through a point reference.

8838-48, Session PMon

Improvement of active lap in the grinding of a 1.8m honeycomb primary mirror

Haitao Liu, Zhige Zeng, Fan Wu, Bin Fan, Yongjian Wan, Institute of Optics and Electronics (China)

The computer controlled active lap (CCAL) is used to grind a 1.8m honeycomb primary mirror now. One problem which is not totally solved of CCAL is the edge effect, which also exists in many other fabricating methods. To reduce the CCAL's edge effect, we analyze the pressure distribution on the contact face between lap and mirror by finite element method (FEM). A new method is proposed to calculate the pressure curve from FEM results. A simplified model is used to approximate the pressure curve along the mirror's radius when active lap covers the mirror's center hole. The const-linear (C-L) model is used to describe the pressure curve when active lap overhang at the mirror's out edge. The contact status between lap and mirror is also considered in this paper, and its influence is taken into the material removal rate's calculation. The API's T3 laser tracker is used to measure the mirror's surface shape and check the theory model's correctness. The results that we have got by now and the problems that still exist are reported in this paper.

8838-49, Session PMon

High-accurate subaperture testing

Fengtao Yan, Institute of Optics and Electronics (China) and Univ. of the Chinese Academy of Sciences (China); Bin Fan, Xi Hou, Fan Wu, Baiping Lei, Institute of Optics and Electronics (China)

We introduced a high accurate subaperture testing method. This stitching method could reduce the interferometers deviation to the stitching results. This high accurate subaperture testing is determined by the data processing technique based on multiangle averaging method and Zernike polynomial fitting method. This technique does not require any assumptions about the surfaces under test. This high accurate subaperture testing method can obtain not only the full absolute shape of the large mirrors but also the reference mirror surface shapes.

The error that the reference affect to the stitch result is only variations and rotationally symmetric of the reference surface deviation. First we describe the detail theory to get the reference surface deviation. Then we provide a comparative experimental study on the high accurate subaperture stitching testing with the QED Technologies method.The experiment results shows that the reference mirror surface shapes could be calibrated and the root mean square (RMS) between the two methods are ~0.80nm and ~0.87nm in the residual figures.

8838-21, Session 5

Fast manufacturing of E-ELT mirror segments using CNC polishing

Caroline Gray, Robert Evans, Nathan R. Field, Paul C. Rees, Steven Waine, Tony Fox-Leonard, Glyndwr Univ. (United Kingdom); David D. Walker, Glyndwr Univ. (United Kingdom) and Zeeko Ltd. (United Kingdom) and Univ. College London (United Kingdom); Guoyu Yu, Glyndwr Univ. (United Kingdom) and Univ. College London (United Kingdom); Wilhelm Messelink, Zeeko Ltd. (United Kingdom) and Univ. College London (United Kingdom)

We report on the first-ever demonstration of grinding and polishing full-size, off-axis aspheric, mirror segments as prototypes for an extremely large telescope, processed entirely in the final hexagonal shape. We first describe the overall strategy for controlling form and mid spatial frequencies, at levels in the vicinity of <10nm RMS surface. This relies first on direct CNC grinding of the base-form of these 1.4m segments, using the Cranfield BoXTM machine. The segments are then mounted on a bespoke support system, and CNC polished on a Zeeko IRP 1600 machine using a variety of custom tooling. We overview the full-aperture and sub-aperture metrology techniques used to close the process-loop and certify quality, all of which operate with the segment in-situ on the IRP1600. We then focus on the pristine edge-definition achieved by the combination of specialist tooling and tool control; results never previously demonstrated on full-size pre-cut hexagonal segments. Finally, the paper discusses the feasibility of scaling the process to deliver 931 segments in seven years, as required for the E-ELT project.

8838-23, Session 5

The development of stacked core technology for the fabrication of deep lightweight UV-quality space mirrors

Gary W. Matthews, Exelis Visual Information Solutions (United States); Charles S. Kirk, Steven P. Maffett, ITT Exelis (United States); Calvin E. Abplanalp, Jet Propulsion Lab. (United States); H. Philip Stahl, Michael R. Effinger, NASA Marshall Space Flight Ctr. (United States)

The ASTRO2010 Decadal Survey stated that an advanced large-aperture ultraviolet, optical, near-infrared (UVOIR) telescope is required to enable the next generation of compelling astrophysics and exoplanet science; and, that present technology is not mature enough to affordably build and launch any potential UVOIR mission concept. Under Science and Technology funding, NASA's Marshall Space Flight Center (MSFC) and ITT Exelis have developed a more cost effective process to make up to 4m monolithic spaceflight UV quality, low areal density, thermally and dynamically stable primary mirrors. A proof of concept mirror was completed at ITT Exelis and tested down to 250K at MSFC which would allow imaging out to 2.5 microns. The parameters and test results of this concept mirror will be shown. The scale-up process will be discussed and the technology development path to a 4m mirror system by 2018 will also be outlined.

8838-24, Session 5

Advancements in asphere manufacturing

Scott DeFisher, OptiPro Systems (United States)

Aspheric optics can pose as a challenge to the manufacturing community due to the surface shape and level of quality required. The aspheric surface may have inflection points that limit the usable tool size during manufacturing, or there may be a stringent tolerance on the slope for mid-spatial frequencies that may be problematic for sub-aperture finishing techniques to achieve. As aspheres become more commonplace in the optics community, requests for more complex aspheres have risen.

OptiPro Systems has been developing technologies to create a robust aspheric manufacturing process. Contour deterministic microgrinding is performed on a Pro80 or eSX platform. These platforms utilize software and the latest advancements in machine motion to accurately contour the aspheric shape. Then the optics are finished using UltraForm Finishing (UFF), which is a sub-aperture polishing process. This process has the capability to adjust the diameter and compliance of the polishing lap to allow for finishing over a wide range of shapes and conditions. Finally, the aspheric surfaces are qualified using an OptiTrace contact profilometer, or an UltraSurf non-contact 3D surface scanner. The OptiTrace uses a stylus to scan across the surface of the part, and the UltraSurf utilizes several different optical pens to scan the surface and generate a topographical map of the surface under test. This presentation will focus on the challenges for asphere manufacturing, how OptiPro has implemented its technologies to combat these challenges, and provide surface data for analysis.

8838-25, Session 5

Designing, fabricating, and testing freeform surfaces for space optics

Xue-jun Zhang, Changchun Institute of Optics, Fine Mechanics and Physics (China)

Freeform surfaces provide more design freedoms to imaging system without introducing new types of aberrations, therefore better performance can be expected.

First in this talk, the design theory of imaging optical system with freeform surfaces was introduced and issues such as tolerancing , manufacturability were discussed; Based on that, fabrication and testing of freeform surfaces were discussed; Particularly?deterministic polishing techniques including CCOS, Magnetic Medium Assisted and Ion Beam polishing were presented in detail.

Since testing is critical to make high accuracy freeform surfaces, the talk also addressed several testing techniques for different fabrication processes varying from rough grinding to fine polishing. Computer Generated Hologram (CGH) design and implement to measure large freeform mirrors were discussed in detail.

Finally, some real world examples were given to show the advantages of freeform surfaces in space optics.

8838-26, Session 5

Ultra-high-precision alignment technology for lens manufacturing used for high-end optics

Thomas Sure, Technische Hochschule Mittelhessen (Germany); Sebatian Schiffner, Hexagon Metrology GmbH (Germany)

We present a way to enhanced common used alignment-technologies by using digital image processing. This work is motivated by the continuously increasing demand for high-end optics. During the last years the surface lens quality has been continuously improved. Today the image quality is more determined by the manufacturing tolerances for the mechanical interface which is responsible for decenter and tilt of the lenses respectively the subgroups. Some of the aberrations are directly linked to the decenter of the lenses, Coma for example. Hence it is necessary to realize the subgroups with tolerances below 1 micron. To determine the decenter of a lens an auto collimation telescope is used to image the reflex of the lens surfaces onto a detector, commonly a half covert photodiode. Rotating the lens generates a sinusoidal signal, which is evaluated by a lock-in amplifier to drive two actuators to adjust the alignment chuck. Typical internal reflections caused by stray light for example disturb the current procedure in such a way that is impossible to get a stable alignment process. Digital image processing allows us to fix these problems with image recognition. We will demonstrate how a modified auto collimation telescope in combination with the developed software algorithms made the manufacturing process more accurate, faster and useable for a broad spectrum of lenses. It has been proofed by some thousand diverse lenses that with these new technique subgroups can be centered within 0.25 microns.

8838-27, Session 6

Development of hybrid fluid jet/float polishing process

Anthony T. Beaucamp, Chubu Univ. (Japan) and Zeeko Ltd. (United Kingdom); Yoshiharu Namba, Chubu Univ. (Japan); Richard R. Freeman, Zeeko Ltd. (United Kingdom)

On one hand, the CNC “fluid jet polishing” process consists of pumping a mixture of water and abrasive particles to a converging nozzle, thus generating a polishing spot that can be moved along a tool path with tight track spacing. But whilst tool path feed can be moderated to ultra-precisely correct form error on freeform optical surfaces, surface finish improvement is generally limited to ~1.5nm rms (with finer abrasives).

On the other hand, the “float polishing” process consists of a tin lap having many concentric grooves, cut from a flat by single point diamond turning. This lap is rotated above a hydrostatic bearing spindle of high rigidity, damping and rotational accuracy. The optical surface thus floats above a thin layer of abrasive particles. But whilst surface texture can be smoothed to ~0.1nm rms (as measured by atomic force microscopy), this process can only be used on flat surfaces.

This paper reports on the development of a novel finishing method that combines the advantages of “fluid jet polishing” (i.e. freeform corrective capability) with “float polishing” (i.e. super-smooth surface finish of 0.1nm rms or less). To come up with this new “hybrid” method, computational fluid dynamic modeling of both processes is being used to characterize abrasion conditions and adapt process parameters of experimental polishing equipment, including: (1) geometrical shape of nozzle, (2) position relative to the surface, (3) dynamic control of inlet pressure. This new process is aimed at next generation X-Ray / Gamma Ray focusing optics.

8838-28, Session 6

Roughness improvement in Active Fluid Jet Polishing (A-FJP) by optimisation of the polishing pin

Manuela Falter, Christine Wünsche, Rolf Rascher, Markus Schinhaerl, Hochschule Deggendorf (Germany)

A testing series was carried out to determine the distribution of the surface roughness across the width of the polishing area when the A-FJP tool is moved on the workpiece surface without overlapping. For the testing series, N-BK7 was used as sample with a diameter of 60 mm. The track of the A-FJP tool is clearly visible. The polishing pin had a diameter of 6 mm and the nozzle had an eccentricity of 1.5 mm. The rotational speed of the nozzle was 1407 rpm and the feed rate was 13.6 mm/min. A standard cerium polishing fluid was used. The pressure at the nozzle was 1 bar.

A Zygo NewView 7200 white light interferometer was used to measure the surface roughness at 5 points across the width of the polishing track. In the second testing series a 2 mm hole was drilled through the centre of the polishing pin so that the polishing fluid not only could stream through the annular gap between pin and nozzle but also straight through the pin.

As the surface roughness could be significantly improved during the testing series with the perforated polishing pin, it stands to reason that the surface roughness in an entire polishing procedure where overlapping takes place may be reduced as well. Further investigations in this area are currently going on to find optimum process conditions between the different parameters, in particular the track distance. If the track distance could be increased, the process time would decrease which in turn would benefit an enhanced economical process.

Results from a simple optimisation of the polishing pin by drilling a hole through its centre have shown a significant improvement of the surface roughness. Additional testing series are currently under way to find out coherences between pin geometry, velocities, track pitch and polishing fluid condition, in particular fluid pressure.

8838-29, Session 6

Fourth-generation aluminum optics performance

Keith Carrigan, Ankit Patel, L-3 Communications Tinsley Labs. Inc. (United States)

While post-polish has previously been shown to greatly enhance the surface quality, surface roughness, and surface figure of single-point diamond turned Aluminum mirrors, the field of bare Aluminum polishing continues to advance. New results demonstrating improvement in mid-spatial frequency errors and methods for adapting to a wider range of Aluminum materials constitute the next generation of polished Aluminum mirrors. These results show new levels of surface finish, correlated with BRDF measurements. Complimentary enhancements have been made by achieving new levels of precision in the placement of the optical axis relative to datum features, enabling significant alignment time savings.

8838-30, Session 6

Novel reactive chemical mechanical polishing technology for fabrication of SiC mirrors

Rajiv Singh, Arul C. Arjunan, Kannan Balasundaram, Sinmat, Inc. (United States)

Silicon carbide (SiC) is considered an excellent material for high performance optical applications because of its superior properties including extremely high specific stiffness (E/ρ), high thermal conductivity and excellent dimensional stability. However, silicon carbide is next only to diamond in hardness and is chemically inert. Both the precision

machining required for shaping and the conventional finishing processes (lapping, polishing) of SiC mirrors is extremely slow making it expensive to produce a light weighted, super-polished SiC substrate. In addition, diamond which is typically employed to achieve reasonable polishing rate, creates sub-surface damage, high density of scratches and other polishing defects which leads to mid and high spatial frequency errors. This talk will focus on a novel reactive chemical mechanical polishing process for SiC mirrors which increases the removal rate by several folds over conventional process at the same time reduce the rms roughness to <0.5 nm. Challenges associated with polishing of polycrystalline SiC and multiple phase material e.g. grain delineation will be discussed. The effect of various components, chemical and mechanical, of the reactive polishing slurry on surface roughness will be discussed.

8838-31, Session 6

Super-smooth optical fabrication controlling high-spatial frequency surface irregularity

Javier G. Del Hoyo, Dae Wook Kim, James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States)

Modern advanced optical systems often require challenging high spatial frequency surface error control during their optics fabrication processes. While the surface figure (>>1mm scales) error can be controlled by directed material removal processes such as small tool figuring, surface finish (<<1mm scales) is controlled with the polishing process. For large aspheric optical systems, surface figure irregularities of a few millimeters in scale may cause serious performance degradation in terms of scattered light background noise and high contrast imaging capability. The conventional surface micro roughness concept in Root Mean Square (RMS) over a very high spatial frequency range (e.g. RMS of 0.5 by 0.5 mm local surface map with 500 by 500 pixels) is not sufficient to describe or specify these surface characteristics. For various experimental polishing conditions, we investigate the process control for high frequency surface errors with periods up to ~2-3mm. The Power Spectral Density of the finished optical surfaces has been measured and analyzed to relate various computer controlled optical surfacing parameters (e.g. polishing pressure, lap stroke speed, polishing compounds) with the high spatial frequency errors on the surface. The experiment-based optimal polishing conditions and processes producing a super smooth optical surface while controlling surface irregularity at the millimeter range are presented.

8838-33, Session 7

Accurately measuring dynamic coefficient of friction in ultraform finishing

Dennis E. Briggs, Samantha Echaves, Brendan Pidgeon, Nathan Travis, Jonathan D. Ellis, Univ. of Rochester (United States)

UltraForm Finishing (UFF) is a deterministic subaperture computer numerically controlled grinding and polishing platform designed by OptiPro Systems. UFF is used to grind and polish a variety optics from simple spherical to fully freeform, and numerous materials from glasses to optical ceramics. The UFF system consists of an abrasive belt around a compliant wheel that rotates and contacts the part to remove material. This work aims to accurately measure the dynamic coefficient of friction (μ), how it changes as a function of belt wear, and how this ultimately affects material removal rates. The coefficient of friction has been examined in terms of contact mechanics and Preston's equation to determine accurate material removal rates. By accurately predicting changes in μ, polishing iterations can be more accurately predicted, reducing the total number of iterations required to meet specifications. We have established an experimental apparatus that can accurately measure μ by measuring triaxial forces under translating loading conditions. Using this system, we will demonstrate μ measurements for UFF belts during different states of their lifecycle and assess the material removal function from spot diagrams as a function of wear. Ultimately, we will use this system for qualifying belt-wheel-material combinations to develop a spot-morphing model to better predict instantaneous material removal functions.

8838-34, Session 7

Analysis and modeling of tribology effects in conventional glass polishing

Daniel Waechter, Olaf Dambon, Fritz Klocke, Fraunhofer-Institut für Produktionstechnologie (Germany)

Conventional or chemo-mechanical polishing represents the polishing technology most often applied for manufacturing precision glass optics. It is applied on various machine types and for all kinds of geometries. But it still represents the manufacturing step with the lowest process stability.

This work deals with the analysis and descriptive modeling of the tribology effects and contact conditions occurring in the process area. The polishing process is assumed as a hydrodynamic system. The model aims for an estimation of the occurring fluid between pad and surface. Its effects on the interaction between the components of the polishing system (pad, slurry, and lens) are discussed. Therefore, existing models are reviewed and combined by the hydrodynamic modeling approach. Secondly, the theoretical considerations are validated by experiments on a specialized tribometer. With this test bench the effects of the viscosity of the slurry, the polishing parameters as well different pad properties on the contact conditions were investigated. It was found, that an increased viscosity as well as roughness of the pad surface shift the transition point between mixed and liquid friction. A focus is put on the polishing pad and the effects of its properties. Four types of the commonly used polyurethane pads were characterized. The process and wear behavior were investigated on a synchrospeed polishing machine, which will be discussed finally based on the findings of the tribometer tests.

The understanding of the contact condition forms the basis for developing stable polishing conditions and improved polishing systems, for example polishing pads.

8838-35, Session 7

Four-axis single-point diamond machining of arrays of miniature lenses

Brian P. McCall, Tomasz S. Tkaczyk, Rice Univ. (United States)

Four-axis single point diamond machining (4-axis SPDM) is a diamond machining technique that executes the spiral toolpath in (X,Y,Z) coordinates of a micro-milling operation while holding the tool in contact with the surface of the lens for the duration of the cut by means of a 4th axis - the C axis. This feature of 4-axis SPDM allows feed rates to be increased without affecting the surface roughness of the finished part, unlike micro-milling. Following errors and inertia become the limiting factor in fabrication speed. This work explores the effect of these dynamics on lens shape and image quality for various geometries of lenses, including spheres, aspheres, convex, and concave lenses. Feed rates are pushed above the previously reported 500 mm/min rates to their limit while maintaining diffraction limited form errors. Plastic materials such as Zeonex 480R and polystyrene Rexolite 1422 are used to create optical components for these experiments. Their surface measurements and imaging properties are shown to confirm the high precision obtained while characterizing the fabrication speeds of the 4-axis SPDM technique.

8838-37, Session 7

A comparison of equivalent moldable glasses

Alan Symmons, LightPath Technologies, Inc. (United States)

There are over one hundred types of glass that are sold as moldable grades. These moldable glasses are manufactured by a limited number of suppliers; each manufacturer with his own grade and designation. Many of these grades can be found to have groupings across the manufacturers, indicating possible equivalency. Equivalency of materials is an important consideration for an optical system as it would eliminate dependency on a single source, and generate cost competition. In order to establish optical equivalency it is necessary to establish significant similarity between materials. This paper compares moldable glass grades from several equivalent glass types from different manufacturers both theoretically and experimentally. Experimental data is based on precision glass molding of the same lens using different but equivalent grades of glass and using standard lens criteria for comparison. Conclusions on whether specific glass types are truly equivalent are then established.

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8839-1, Session 1

Spatial fringe analysis based on FFT using only two speckle pattern in ESPI *(Invited Paper)*

Yasuhiko Arai, Kansai Univ. (Japan)

Speckle interferometry is one of important deformation measurement methods for an object with rough surfaces. Many methods have been already reported. In this paper, a high resolution new measurement method which requires only two sheets of speckle patterns in analyzing process is proposed. In the method, a new optical system which uses a plane wave-front as the reference beam of the speckle interferometer is employed. In the fringe analysis by using the optical system, the deformation information and the bias components of the speckle patterns can be clearly separated in frequency domain. A pair of real- and imaginary-part components concerning the information of deformation can be extracted by Fourier transform in the fringe analysis processing. The real part of the information before deformation is shifted on the frequency domain in order to create carrier fringes. Furthermore, the specklegram is calculated between the shifted real part of the speckle-pattern before deformation and the non-shifted real part of the speckle-pattern after deformation. The fringe image, which includes the spatial carrier-information, is given as specklegram, and is filtered. The phase map is calculated by using spatial fringe analysis method from the filtered deformed carrier fringes as specklegram. From experimental results, it is confirmed that the new method can analyze a deformation process with a convex and/or concave phase distribution in a high resolution power, and that the resolution power of the measurement is much higher than 1/150 of the light source of the optical system.

8839-2, Session 1

Real-time uniaxial profilometry using contrast detection by polarization camera

Yukitoshi Otani, Shuhei Shibata, Fumio Kobayashi, Utsunomiya Univ. (Japan); Yasuhiro Mizutani, Univ. of Tokushima (Japan); Toru Yoshizawa, NPO 3D Associates (Japan)

We propose a real time measurement of three-dimensional surface shape using contrast detection of uniaxial detection by a polarization camera. All distance information of z-direction can be determined by measuring the contrast of projected grating pattern that can be calculated phase-shifting method. A telecentric optical system is employed to keep the magnification of the object image captured by a CCD camera by changing the focus distance. A shadow less measurement of the object's area is archived by using a uni-axial system. The liquid crystal digital shifter is a powerful tool to analyze the contrast that is made arbitrary intensity and frequency distribution. Surface profiles are measured to demonstrate this method.

8839-3, Session 1

Improve dithering technique for 3D shape measurement: phase vs intensity optimization

Junfei Dai, Zhejiang Univ. (China); Beiwen Li, Song Zhang, Iowa State Univ. (United States)

We recently introduced binary dithering techniques to the 3D shape measurement field. These methods have drastically enhanced the binary defocusing technique. Yet, the dithering techniques, after all, are developed to represent arbitrary grayscale images with fewer bits through simple matrix operation. There is not optimization method developed for sinusoidal structured patterns. Therefore, it has great potential to further improve the dithering technique by taking advantage of the inherent sinusoidal structures. The optimization can be performed with in phase or intensity domain. The former is to approximate the ideal phase with the binary patterns after they are slightly blurred; and the latter is to approximate the ideal sinusoidal waveform with the binary patterns. The question to ask is: which optimization method will be more robust? This paper presents a thorough comparison between these two methods. Since a 3D shape measurement system utilizing a digital fringe projection technique, the phase quality ultimately determines the measurement quality, and thus these methods are compared in phase domain. Both simulation and experiments find that the phase-based optimization method can generate high-quality phase under given conditions. However, this method is sensitive to the amount of blurring (or defocusing). On contrast, the intensity-based optimization method can consistently generate high-quality phase with various amounts of defocusing. Therefore, it seems that the intensity-based optimization method has more practical value than the intensity-based optimization method in the 3D shape measurement field.

8839-4, Session 1

Dual resolution imaging for metrology applications

Kevin G. Harding, Daniel C. Gray, GE Global Research (United States)

Many applications require a fine measurement to be made over a small area, but with reference to a much larger area. The ability to inspect a large surface, then to zoom in to a small area is valuable in many application ranging from bridges to turbines. However, the need to switch lense or re-point a lens can make such inspection cumberson. This paper discusses an optical method that permits an instantaneous switch from a wide view to a close up of any area within that wide view, without the need to change lenses or repoint the optical system. We will discuss the possible application of the method, as well as the limitations inherent to the concept.

8839-5, Session 2

Surface profile measurement of a diffraction grating by a laser beam scanning interferometer using sinusoidal phase modulation *(Invited Paper)*

Osami Sasaki, Takuya Kubota, Samuel Choi, Takamasa Suzuki, Niigata Univ. (Japan)

It is difficult in interferometric metrology to maintain high spatial resolution over a large measurement region. Interferometric microscope measurements yield high resolution, but only over a small area. Other conventional interferometric systems can measure large areas, but they fail to provide the necessary spatial resolution. High spatial resolution over a large field of view is a very important characteristic for large size objects. In this paper this characteristic is achieved by scanning a focused laser beam over an object surface and a reference mirror surface in an interferometer for surface profile measurement. A collimated laser beam from a laser diode is incident into an electric-optic phase modulator (EOM) to generate sinusoidal phase-modulation between the two orthogonal polarization components. The beam passing through the EOM is reflected by a rotating mirror and moves over a surface of a polarization beam splitter with the help of a lens to produce a focused beam scanning over an object surface and a reference mirror surface. When the object is a diffraction grating, the beam focused on to the grating is not diffracted strongly. This effect leads to an easy and exact measurement without an imaging system in the interferometer. The two focused beams are reflected by the surfaces and travel back along the same path as the original beam. A confocal optical system with a lens and a pinhole is used to produce a sinusoidally phase-modulated interference signal on a photo-multiplier detector. In experiments, the scanning speed of the focused beam was 20 m/s, and the frequency of the sinusoidal phase-modulation was 10 MHz. The spatial resolution of the surface profile measurement was 2.0 microns over the measurement area of 15mm. The measurement results indicated that the measurement error was less than 5nm.

8839-6, Session 2

Diffractive optics calibrator

Wenrui Cai, Ping Zhou, Chunyu Zhao, James H. Burge, The Univ. of Arizona (United States)

Errors and uncertainties in the fabrication processes of diffractive optics will produce wavefront phase errors. When applying the finished part in optical testing, accuracy of the measurements will be affected consequently. In this paper, we describe the diffractive optics calibrator, a new device for measuring the local duty-cycle and etching depth of a binary diffractive optics used in transmission. The measurements can be used to assess uniformity of the diffractive optics for calibration or quality control.

According to scalar diffraction theory, diffraction efficiency is a function of both the duty-cycle and the etching depth of a binary linear grating. We utilize this relationship in the device. From a collimated laser beam, the intensities of multiple diffraction orders were captured by wide field of view camera lens. The duty-cycle and etching depth are determined simultaneously by fitting the measured intensities to a parametric model. This device is able to scan through the whole area of the diffractive optics and generate a wavefront phase error map, which is due to duty-cycle and etching depth variations. The measurements are validated with a lateral scanning white-light interferometer.

The system is capable of measuring the percentage of duty cycle variation that causes 1 nm PV phase errors. This method is advantageous since it can be carried out rapidly with accurate and repeatable results, does not damage the sample, and uses low-cost equipment.

8839-7, Session 2

Comparison between LCOS projector and DLP projector in generating digital sinusoidal fringe patterns

Beiwen Li, Song Zhang, Iowa State Univ. (United States)

In digital fringe projection technique, digital sinusoidal fringe patterns of good quality need to be generated in order to perform an accurate measurement. There are two major ways to generate digital sinusoidal fringe patterns: focused-sinusoidal-patterns (FSP) method and defocused-binary-patterns (DBP) method. The performances of both FSP and DBP technology are subject to the properties of the projector used. Digital-light-processing (DLP) and liquid-crystal-on-silicon (LCOS) are two widely used digital projection technologies which have drawn great attention from researchers. They have different ways to generate grayscales. For DLP technology, it works with digital micro mirrors and the different grayscales are generated by time integration, while for LCOS technology, it works with liquid crystals instead of individual mirrors. It has already been studied that for DLP technology, when FSP method is applied, it suffers from nonlinear gamma effect as well as varying phase error over different exposure times, while DBP method does not have such drawbacks. Then a question is raised: is there any difference for LCOS technology? Do the aforementioned problems become ameliorated or worse? This paper presents a comparison between LCOS and DLP projector for FSP method, DBP method as well as projector nonlinear gamma. Experiment depicts that for FSP method, LCOS projector has advantages over DLP for its smaller nonlinear gamma effect and no need for precise synchronization. While for DBP method, DLP projector is superior to LCOS projector for its generated patterns of higher contrast ratio.

8839-8, Session 2

Characterization of the optical components fabricated by femtosecond pulses in transparent materials

Lina Mazule, Simona Liukaityte, Vilnius Univ. (Lithuania); Vytautas Sabonis, Vilnius Univ. (Lithuania) and Workshop of Photonics (Lithuania); Titas Gertus, ALTECHNA Co. Ltd. (Lithuania); Mindaugas Mikutis, Vilnius Univ. (Lithuania) and Workshop of Photonics (Lithuania); Domas Paipulas, Tomas Puod?i?nas, Valdas Sirutkaitis, Vilnius Univ. (Lithuania)

The femtosecond laser pulses found wide application in modification of the refractive index or surface topography of the transparent materials. These modifications created new generation of optical components: diffraction gratings and radial polarization elements fabricated in fused silica, solar cells and etc. The operation and quality of these components depend on laser and processing parameters. Sensitive and multiple methods are required for characterization of these optical components and optimization of the modification process.

We present the optical methods used for characterization of the diffraction gratings and radial polarization elements fabricated in fused silica by high repetition rate femtosecond KGW:Yb laser. The methods used for characterization of the components with refractive index modification were transmission and diffraction measurements at fixed and tunable wavelengths, and total integrated scattering (TIS). Transmission and diffraction measurements were performed by photodetectors and CCD camera using tunable radiation from OPA “Topas”. Solar cells with modified surface by femtosecond pulse ablation were investigated by TIS and Volt-Ampere measurements.

The combined characterization methods were sufficient for modification process optimization and allowed creation of the Bregg gratings with efficient in range from 55 to 90% and low scattering losses.

The current increase is registered with growth of the scattering loses in the solar cells. Volt-Ampere measurements showed that there is great improvement of scattering light comparing laser unaffected zone and laser fabricated zone with 1.1 uJ pulse energy and 10 um between pulses (from 4.04% to 21.9%).

8839-10, Session 3

Coaxial phase-shifting laser diode interferometer based on pulse modulation *(Invited Paper)*

Takamasa Suzuki, Takuma Serizawa, Osami Sasaki, Samuel Choi, Niigata Univ. (Japan)

The optical interferometer is an important device in precision manufacturing. The wavelength tunability of laser diodes (LDs) is a useful parameter to consider when configuring a compact interferometer. Several types of interferometers that employ LDs have been proposed and used in practical applications. Although the LD wavelength is generally modulated using a stepwise, triangular, or sinusoidal signal, this direct modulation degrades the measurement accuracy because the intensity of the interference signal varies with the injection current.

We previously proposed a phase-shifting (PS) interferometry that uses a pulse current for direct modulation. The wavelength change that occurs just after the injection of a pulse current is used to modulate the phase of the interference signal. This technique enables accurate phase measurement as it realizes a large wavelength change with no change in optical power. In the optical system, however, it requires the use of two separate interferometers to determine the amount of phase shift accurately. Also it takes time for capturing images if no ultrafast camera is available. These restrictions make the system vulnerable to external disturbances.

In this paper, we propose a pulse-modulated PS interferometer, in which two coaxial interferometers and an undersampling technique are employed. The former improves the robustness of the optical system and the latter shortens the time of image capture. Several measurements on a flat mirror confirmed a measurement accuracy of ~20 nm.

8839-11, Session 3

Research on a fiber Bragg grating sensor structure for health monitoring of coal mines

Yong Zhao, Yue Dong, Zhongqiang Li, Northeastern Univ. (China)

The coal mine tunnel collapse problem is very common and its damage is very serious. At Present, few researches are done about the engineering design of the optical fiber sensor and the analysis of the sensor monitoring system. In this paper, a displacement sensor using fiber grating technology was designed, which could be used to prevent the problem of coal mine tunnel collapse by monitoring the coal mine tunnel roof displacement. Firstly, The Finite Element Analysis was demonstrated to simulate the stress and displacement of coal mine tunnel roof to determine where to install the sensor. Then the characteristics of the fiber Bragg grating sensor were analyzed in detail and the sensor structure was designed according to the actual requirements in the coal mine. At last, the feasibility of the whole system was experimentally verified. The specific sensor structure design was as follows: the mine tunnel roof were fixed with two anchors, a spring and a two-period fiber grating were placed in series to achieve displacement measurement between two anchors. In this structure, one end of the spring was connected to the first anchor, and the other end was connected with the two-period fiber grating. What's more, the second end of the fiber Bragg grating was connected to the second anchor. The cross-sensitivity of temperature and displacement issue with FBG sensors could be eliminated by this special design. The measuring range of 100mm and the measurement accuracy up to 0.1mm could be obtained with the proposed sensor.

8839-12, Session 3

Using fiber-optic probes for photoluminescence and evaluation of an InGaN/GaN epi-wafers

Woohyun Jung, Jongki Kim, Hang-Eun Joe, Byung-Kwon Min, Kyunghwan K. Oh, Yonsei Univ. (Korea, Republic of)

Photoluminescence (PL) is one of the methods used for analyzing the optical characteristics of LED epi-wafers. For components in solid-state lighting such as GaN-based LEDs, the use of an LED structure configuration on a patterned sapphire substrate has shown to be highly effective in improving light-extraction efficiency. We constructed a simplified PL measurement system based on fiber-optic probes to enhance the efficiency of PL analysis. An excitation beam was launched from 405nm laser using the lensed fiber fabricated by splicing a single-mode fiber and a polymer-coated coreless silica fiber. For high resolution, a multi-mode file detector tip was manufactured using a focused ion beam. The 38μm diameter core of this tip is coated with a 30nm Au film, with a 1.0μm diameter centered hole. The relative importance of both contributions and the achievable lateral resolution are strongly dependent on the geometry and scanning conditions. A computer-controlled xyz nano-positioning stage was used to move the samples. With this system, we successfully obtained PL morphology data from peak intensity, peak wavelength (photon energy) and FWHM of the emission spectra at each position on the epi-wafers. The proposed fiber-optic PL system could become a compact and multifunctional alternative method to pre-existing PL systems. We also expect that further optimization of the focused beam diameter could improve the spatial resolution of the system, and hope that a completed system will analyze surface condition, alloy composition change, variation in layer thicknesses and layer disorder / grading effects.

8839-13, Session 3

OCT based on multi-frequency sweeping Fizeau Interferometer with phase modulating method

Samuel Choi, Osami Sasaki, Tomoya Watanabe, Takamasa Suzuki, Niigata Univ. (Japan)

Recently, the demands for tomographic vibration measurements with sub-nanometer accuracy using the optical coherence tomography (OCT) technique have increased in the biomedical field. We proposed a Multi-frequency sweeping Fizeau-type interferometer (MFS-FI) for the OCT. The multi-frequency sweeping by a variable Fabry-Perot filter (FPF) permits detection of high-order low-coherence interferometric signals in the Fizeau interferometer. The sinusoidal phase modulation (SPM) technique was utilized to detect accurate interference amplitude and phase distributions of back scattered light from surfaces of a sample. The experimental setup of the MFS-FI consisted of a super luminescent diode with center wavelength and bandwidth are 840 nm and 30 nm respectively, collimator, the FPF, a Fizeau interferometer and a 2-dimensional CCD image sensor. The interference image from a sample is focused by using a lens system. The FPF in which a cavity length was scanned by a Piezo-electric (PZT) actuator produced the multi-frequency sweeping for depth scan. The SPM was performed by modulating the path difference using a PZT to detect the interferometric phase. The SPM signal was driven by a signal generator of which the modulation frequency was synchronized with a flame rate of the CCD. The samples were glass plates and tissues fixed with formalin and embedded in paraffin vibrated with a frequency of few ten kHz. By using the MFS-FI with the SPM, we could measure the tomographic 3-dimensional volume of the samples and estimated its vibrating surface displacement with an accuracy of nanometers.

8839-14, Session 4

Multimodal industrial inspection in power engineering and building industries: new challenges and solutions *(Invited Paper)*

Malgorzata Kujawinska, Warsaw Univ. of Technology (Poland)

This presentation will cover digital image correlation, thermography, structured light methods with spectral and roughness analysis (I might add also local interferometric sensors). I will also present several interesting examples of usage these techniques in power engineering and building industries.

8839-15, Session 4

Automated cylindrical mapper using chromatic confocal measurement

Esmaeil Heidari, Kevin G. Harding, Robert W. Tait, GE Global Research (United States)

Characterization of a surface shape and finish has been vital for the manufacture of precision parts. Overall profile, surface finish and waviness of a part can be measured in two ways, contact and non-contact. In the contact method a stylus is dragged on the surface of a part to measure the profile and texture of the part for quantifying the surface characteristics. Non-contact methods applied to precision metrology include: microscopy, interferometry, chromatic confocal microscopy and laser profiling such as structured light methods. The chromatic confocal method offers flexibility because of its fiber optics probes that can be manipulated to accommodate many sample geometries. This flexibility provides a wide range of possible analysis dimensions such as cylindrical shapes of holes and the potential to provide both surface roughness and shape. This paper will discuss the setup and testing of a system specifically for measuring cylindrical shaped parts and present the performance of the technology as a precision metrology tool.

8839-16, Session 4

Calibration of high-aspect ratio quality control optical scanning system

Aneliya Karadzhinova, Timo Hilden, Jouni Heino, Helsinki Institute of Physics (Finland); Maria Berdova, Aalto Univ. and Micronova Nanofabrication Ctr. (Finland); Rauno Lauhakangas, Francisco Garcia, Eija Tuominen, Helsinki Institute of Physics (Finland); Ivan Kassamakov, Univ. of Helsinki (Finland)

Gas electron multiplier (GEM) detectors are widely used in contemporary high energy physics experiments, e.g. at the European Organization for Nuclear Research and Antiproton and Ion Research in Europe experiments. The GEM is a detector containing an etched holes in the polymer foil coated with a thin metal layer on both sides which is able to achieve high amplification gains and performance at low cost, even under harsh radiation conditions. The foil holes have with nominal diameter of 70 ±5 µm and 140 µm between centre separations.

A high quality assurance is needed to guarantee a long lifespan for the detectors in the severe radiation environment. Mapping of the defects connecting two or more holes is important phase when determining the usability of a foil for detector application.

Optical Scanning System (OSS) with scanning area of 1000 x 1000 mm was realized at the Helsinki Detector Laboratory for control of the quality of GEM foils.

A silicon test sample containing sets of 10 x 10 numbered etched wells with nominal diameter of 70 ±1 µm was produced and was calibrated using factory calibrated Stylus profiler (KLA – Tencor P15). The wells dimensions and the expanded uncertainty were calculated with 95% confidence level, as it is required by the ISO Guide for Expression of Uncertainty in Measurement.

The silicon sample was measured with the OSS in nine different positions of the scanning area. The results were analyzed and uncertainty and the corrections were calculated according to the ISO requirement.

8839-17, Session 4

One-shot measurement of the air-liquid interface effect by a spectral-domain low-coherence dynamic light scattering technique

Toshiharu Watarai, Toshiaki Iwai, Tokyo Univ. of Agriculture and Technology (Japan)

The Brownian motion of particles close to the interface between air and liquid is affected by the hydrodynamic interaction due to Stokes drag force. The particles move considerably slower in this region than in the free diffusive region far from the fluid surface. The experimental setup was constructed as an optic-fiber Michelson interferometer with a low-coherence light source and a high-speed spectrometer. Applying the principle of the spectral-domain optical coherence tomography to the low-coherence dynamic light scattering, we can realize non-scanning operation of the reference mirror in the depth range. Therefore, the spectral-domain low-coherence dynamic light scattering technique is proposed to analyze the dynamics of the Brownian particles simultaneously and seamlessly at the measuring positions from the far region to the near region. The 1-vol% suspension of the polystyrene latex particle with the sub-micron radius was used as a sample medium in the experiments. The diffusion coefficients can be estimated by fitting numerically a negative-exponential function as a model function to the measured amplitude auto-correlation function of time-varying scattering amplitude. As a result, the experimental diffusion coefficients show that the Brownian motion is suppressed in the region close to the air-liquid interface, increases consistently with the distance from the interface, and is in free Brownian motion far from the liquid surface. The effectiveness and the applicability of the proposed new dynamic light scattering technique can be fairly well confirmed by the experiments.

8839-18, Session 4

Development of blood vessel search system using near-infrared light for laparoscopic surgery

Kazuyuki Narita, Eiji Nakamachi, Yusuke Morita, Akeo Hagiwara, Doshisha Univ. (Japan)

Our objective in this study is to develop a miniature and high accuracy automatic 3D blood vessel searching system, which will be introduced in the laparoscopic operation with the minimally invasive surgery. Now, the conventional optical system used in the laparoscopic surgery have many difficulties of blood vessel imaging and detection, because the peripheral bio-tissue located around the blood vessel disturbs the light wave propagation, disperses and refracts. Consequently, only unclear image is obtained. We develop a new blood vessel detecting system by using Near-Infrared (NIR) light, two CMOS camera modules and a comprehensive image processing technique, which is implemented in the laparoscope pipe with 25mm in diameter. We adopt the stereo method for the searching system to determine 3D blood vessel location. The blood vessel visualization system adopts hemoglobin's absorption characterization of the NIR light, which has high permeability for the bio-tissue and absorbency for the hemoglobin. A sharpening process is employed to improve the image quality of original ones, through the LoG filter and the un-sharp-mask processing. 2D location of the blood vessel is calculated by luminance distribution of the image and its depth is calculated by the stereo method. A validity of our blood vessel visualization and 3D detecting system was examined through the comparison with the imaging and detecting results of organization phantoms, which embedded at known depths under the surface. Experimental results of depth obtained by our detecting system showed good agreements with the given depths, and the availability of this system is confirmed.

8839-19, Session 4

Inch-scale high-throughput metrology of graphene and patterned graphene oxide

Dennis Pleskot, Zafer Mutlu, Jeffrey Bell, Isaac Ruiz, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

Inch-scale high throughput characterization of graphene sheets was achieved by fluorescence quenching microscopy (FQM). This technique proved to be highly scalable compared to other common methods such as Raman spectroscopy, SEM, and TEM. Whereas other techniques can take days to image inch-scale samples, FQM requires only a few hours. Along with this, fluorescence quenching caused minimal, if any, damage to graphene samples, demonstrating the non-destructive nature of this method. In contrast, other techniques such as Raman, SEM, and TEM, are well known for being highly destructive imaging processes. Thus, fluorescence quenching was determined to be a highly advantageous characterization technique for large-area graphene compared to the more common methods currently in use. FQM also displayed effectiveness at imaging the contrast between graphene and graphene oxide, demonstrating an ability to generate distinct contrast intensities for pristine graphene, pristine graphene oxide, defects, and multilayer regions within graphene oxide. Contrast differences due to fluorescence quenching were further analyzed by Raman spectroscopy,

which confirmed the existence of these different intensity regions and thus validated FQM as a reliable characterization process. Since large-area graphene has several potential applications in solar cell devices and macroscale mechanical support structures, and graphene oxide is an important precursor in producing graphene, FQM characterization of these materials is a significant step toward making these applications a reality.

8839-20, Session 5

High-resolution real-time 3D shape measurement on a portable device

Nikolaus L. Karpinsky, Morgan Hoke, Vincent Chen, Song Zhang, Iowa State Univ. (United States)

Recent advances in technology have enabled the acquisition of high-resolution 3D models in real-time though the use of structured light scanning techniques. While these advances are impressive, they require large amounts of computing power, thus being limited to using large desktop computers with high end CPUs and sometimes GPUs. This is undesirable in making high-resolution real-time 3D scanners ubiquitous in our mobile lives. To address this issue, this work describes and demonstrates a real-time 3D scanning system that is realized on a mobile device, namely a laptop computer, which can achieve speeds of 30fps 3D at a resolution of 640x480 per frame. By utilizing a graphics processing unit (GPU) as a multipurpose parallel processor, along with a parallel phase shifting technique, we are able to realize the entire 3D processing pipeline in parallel. To mitigate high speed camera transfer problems, which typically require a dedicated frame grabber, we make use of USB 3.0 along with direct memory access (DMA) to transfer camera images to the GPU. To demonstrate the effectiveness of the technique, we experiment with the scanner on both static geometry of a statue and dynamic geometry of a talking participant in front of the system.

8839-21, Session 5

Uni-axial inner profile measurement

Toshitaka Wakayama, Saitama Medical Univ. (Japan); Toru Yoshizawa, NPO 3D Associates (Japan)

Recently, the requirement of an inner profile measurement has been rapidly increasing to get quality assurances in the fields of industry and medicine. Using a ring beam device our group has proposed the inner profile measurement based on optical sectioning technique. This measuring instrument is very powerful tool to evaluate their inner surface profile and their condition of industrial samples. As advanced evaluations, there is required to measure the inner surface profile of samples at uni-axis. To meet this requirement, we have proposed a uni-axial inner profile measurement based on the technique of shape from focus. In our experiment, we employed a He-Ne laser, a variable focus lens, a conical mirror and a CCD camera. The laser beam was incident into the conical mirror after passing through the variable focus lens. The shape of laser beam was transformed from a point beam to a disk-like beam. The focus of the disk-like beam can be controlled by current value of the variable focus lens. A CCD camera captured the intensity distribution of optical sectioning profile on the inner surface of the sample. The intensity distribution captured by CCD camera became a Gaussian profile along the current value. As this result, the radius distribution on a crossed sectioning profile can be determined. In this manuscript, we have shown some experimental results as demonstrations.

8839-22, Session 5

On-machine laser triangulation sensor for precise surface displacement measurement of various material types

Klemen Žbontar, LPKF Laser and Elektronika d.o.o (Slovenia); Matjaž Mihelj, Univ. of Ljubljana (Slovenia); Boštjan Podobnik, LPKF Laser & Electronics AG (Slovenia); Franc Povše, LPKF Laser and Elektronika d.o.o (Slovenia)

The paper presents a custom-designed laser triangulation based metrology system, which enables high precision surface displacement measurement of various material types with a single sensor configuration. Laser structuring applications require material surface alignment relative to the laser focus position, where fabrication conditions are optimal. The measurement system utilizes a high-quality UV wavelength laser beam (primarily used for structuring purposes) with automatic control of its intensity. The laser source operates in a continuous wave (CW) mode during the measurement process, whereas the UV wavelength enables measurement of transparent materials. Robust displacement measurement of various material types was solved by introducing a new approach of structured light projection and its centroid detection. A high resolution 2D galvanometric scanning system is used for dynamic symmetrical pattern projection, which is proven to reduce the effects of material surface related errors and speckle noise. Furthermore, a “double curve fitting” (DCF) centroid detection algorithm, where Gaussian curves are fitted to radial cross sections of the acquired pattern, and an ellipse is fitted to their peak positions, was introduced. The method includes subsurface scattering compensation, which proves crucial for translucent material measurement, where incident light penetrates into the material surface and causes uneven light intensity distribution of the acquired pattern. Experimental results have shown that the metrology system is robust to laser intensity variation and material type, with measurement bias lower than 50 μm and standard deviation lower than ±6.3 μm for all materials. The developed probe has been integrated into commercial LPKF laser structuring systems.

8839-23, Session 5

Adaptive control system for improvement of contrast in interferograms

Nicolas Veloz, Jesús E. González-Laprea, Rafael Escalona, Univ. Simón Bolívar (Venezuela)

The present work consists of the development proposal of an adaptive control system to compensate the reduction of the contrast in interferograms caused by mechanical vibrations presented in a mirau based interference microscopy system using a low-speed camera as the only sensor. The control scheme generates random signals that are injected during the integration time of the camera through a piezoelectric in order to change the phase of the interferometer, Each image obtained by the low-speed camera has different control signals injected during the integration time. The contrast of each image is evaluated and if the contrast is improved, the signal injected during that image is adjusted to seek for a better improvement. The best signals collected, are added to the control signal, which is applied to the system after the adaptation process is over. This control scheme was implemented and proved to be able to find signals capable to compensate the main frequency components of the vibration in the system, the maximum contrast increment obtained was about 11%

8839-24, Session PMon

Full-field transmission-type angle deviation microscopes

Ming-Hung Chiu, Ming-Hung Tsai, National Formosa Univ. (Taiwan)

We proposed a three-dimensional (3-D) microscope with a magnification of 250X based on the principle of angle deviation microscopy for measuring the 3-D profile of transparent materials. When a parallel beam passing through a specimen, the angle of light after passing each test point will be deflected due to the slope of surface or/and the change of refractive index. The small deflective angle can be acquired using an angular sensor made of a parallelogram prism at the critical angle. Thus, the surface height is proportional to the deflective angle and the reflectivity of the prism. Using two CCDs located at the image planes to detect the image intensities on conditions of TIR and the critical angle, respectively, the profile of reflectivity is obtained and can be transformed into the 3-D profile of the test specimen. In our experiment, the lateral and vertical resolutions can be demonstrated within submicron and 1 nm, respectively.

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8840-22, Session PMon

Mathematical modeling analysis on a small and compact two-dimensional CGLSI interference system

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When using interference wave front to detect density field, it is better to have an interference system which is small and compact so that different directions of wave fronts can be obtained to reconstruct the density field to be detected. A two-dimensional CGLSI (Cross Grating Lateral Shearing Interferometer) system which consists of a two-dimensional cross grating and a two-dimensional order-selecting window used as a filter is presented in this paper. Lateral shearing interferogram of two orthogonal directions (X and Y) each other can be obtained by using this system. With the advantage of anti-vibration and no reference surface, lateral shearing interferometer is suitable to inhibit external environment disturbance. In this paper, analysis and simulations have been conducted on grating constant from geometrical optics and physical optics using Fresnel approximation method respectively based on lateral shearing rate, windows' distance in two-dimensional order-selecting window and layout of the system which concludes the best option for grating constant is . The most optimized design of size and distance for windows in two-dimensional order-selecting window has been carried out on the basis that complex amplitude distribution can go through the filter so that there is no distortion on wave front. All designs have gone through computer simulation and fit into the requirements for the designs.

8840-23, Session PMon

Optical design of non-image optical engine with local-dimming effects via liquid crystal optics and laser light source

Yi-Chin Fang, National Kaohsiung First Univ. of Science and Technology (Taiwan)

The research demonstrates an optical design of non-image optical engine with liquid crystal optics and laser light source, which will deliver the effects similar to local dimming effects from backlight unit . Firstly, in order to achieve high contrast similar to local dimming effects from backlight system design, we employs primary colours of RGB light of laser which is mixed with a X-cube. Secondly, this design employ RGB laser as light sources. With assistance of microscanning technique and liquid optics array, varied contrasts could be presented on illumiated plane thanks to special optical design of each laser source arrays and digital signal processing.This is a completely new design which takes advantage of not only less heat interference and minimization of volumetric size of optical engine but also up to 1:100 contrast if applied to DLP projector. The simulation work reveals the performance and contrast of new developed projector reach success. if applied to DLP projector, The optical design reaches light uniformity is 86.6 % and light energy efficiency is near 40%. local dimming produced by liquid optical element will significantly improve contrast of projector up to 70%.

8840-1, Session 1

Hybrid fast Hankel transform implementation for optics simulation

Paul K. Davis, NASA Ames Research Ctr. (United States)

The most compute intensive part of a full optics simulation, especially including diffraction effects, is the Fourier transform between pupil and image spaces. This is typically performed as a two dimensional fast discrete transform. For a nearly radially symmetric system there are advantages to using polar coordinates, in which case the radial transform becomes a Hankel transform, using Bessel functions instead of circular functions. However, there are special difficulties in calculating and handling Bessel functions. Several solutions have been proposed. We present a hybrid Hankel transform which divides the range, calculating a portion using Bessel function approximations but converting most of the range into a one dimensional Fourier transform which can be handled by standard methods.

8840-2, Session 1

Frequency noise in spectral lineshape of 780-nm GaAsP/GaInP quantum-well lasers for inertial sensor applications

Joseph P. Bebe Manga Lobe, III-V Lab. (France); Bernard P. Orsal, Institut d'Electronique du Sud (France)

On one hand, 100 µm aperture broad area devices achieve at 20°C a continuous wave (CW) output power of more than 4 W per facet. On other hand, we demonstrated excellent performances on Fabry-Perot ridge-waveguide lasers with a threshold current of 35 mA, emitting up to 120 mW per facet, in single lateral mode at 780 nm. We already achieved an output power of 20 mW with a small spectral linewidth of less than 1 MHz on a DFB laser.

We present here the results on a new and systematic investigation of the low frequency noise of such laser structures, in order to better understand and improve their performances.

By using an appropriate current source and very low noise voltage amplifier (10-19 V2/Hz at 10 Hz), we can measure the intrinsic Terminal Electrical Noise (TEN), due to the fluctuations of the laser voltage. The measurements have been performed for low frequency (1Hz < f <100 kHz) and different laser currents (around the threshold current, above and at high laser current). On broad band area lasers, we obtained a very low 1/f level noise (10-13 V2/Hz at 1 Hz) due to optical gain fluctuations and active region noise (shot and thermal noise). The white noise level is about 10-18 V2/Hz . The corner frequency between 1/f and white noise is about 3 KHz, which is a good result for this kind of structures. Electrical noise measurements will be interpreted by using lasers noise theory.

8840-3, Session 1

Nth Stokes evolution due to SRS in single mode fibers

Rafael S. Lara, Ctr de Investigación e Innovación Tecnológica (Mexico); José Alfredo Alvarez-Chávez, Ctr. de Investigación e Innovación Tecnológica (Mexico); Lelio de la Cruz May, Univ. Autónoma del Carmen (Mexico)

In this work, the evolution of the nth analytical solutions of traditional Raman equations including numerical simulation and experimental results is done. In the experiment a 8.6 Km single mode fiber was pumped with an ytterbium doped fiber laser system (FL) in CW regime at 1064-nm in a free running configuration. We showed that it is possible to obtain up to the nth power thresholds and maximum power for each Stokes by using compact analytical solutions such as first approximations in an arguably simple, quick process.

A comparison of different technical analysis of Raman phenomenon was done. We showed how long the analytical and simulation results are approximated to experimental results. The parameter in comparison was power thresholds and maximum power for each Stokes. The comparative graphics have been done in 2 y 3D to show the evolutions of Stokes.

8840-4, Session 1

Circulation and concentration of s- and p-polarized light in two-dimensional compound grating

Young Uk Jung, Andrii B. Golovin, David T. Crouse, The City College of New York (United States)

Two-dimensional compound gratings (2dCGs) are capable of π-radian difference phase resonances (PRs). Circulation and concentration of p- and s- polarized incident beam of the light upon 2dCG metal structures are studied. In prior work, it has been shown that PRs can occur for p- and s-polarized light in one-dimensional compound gratings. In contrast, the structure studied in this work has two asymmetric holes in the unit cell, each filled with a material of high dielectric permittivity (ε=10.84) and can support PRs in 2dCGs in the 8 GHz to 12 GHz spectral range. Due to asymmetry within the system, the two apertures react differently to the incident beam and support PRs that are resonantly excited within the grooves. It is shown that PRs occur in 2dCGs with similar characteristics of 1dCGs, such as having narrow bandwidths, high Q values, and high concentrations of electromagnetic fields. However, PRs occurring on 2dCGs have a benefit of manipulating light in more numerous and compelling ways as compared with 1dCGs. As the incident light excites waveguide cavity modes, the fields in the desired neighboring cavities in 2dCGs are coupled by circulations of counter-propagating modes and the π -radian phase differences produce a concentration and narrowband inversion of the transmissivity/opacity. The dependencies of bandwidth and wavelength of the PRs on structural and material properties, polarization of the incident beam, as well as the Poynting vector profiles are described. Applications include narrow bandwidth optical filters, light trapping, antireflection coatings, waveguiding structures, and electromagnetically induced transparency.

8840-5, Session 2

Ray-tracing-based simulation of stray-light correction for Geostationary Ocean Color Imager

Eunsong Oh, Korea Institute of Ocean Science & Technology (Korea, Republic of) and Yonsei Univ. (Korea, Republic of); Jinsuk Hong, Samsung Thales Co., Ltd. (Korea, Republic of) and Yonsei Univ. (Korea, Republic of); Sug-Whan Kim, Yonsei Univ. (Korea, Republic of); Ki-beom Ahn, Seongick Cho, Korea Institute of Ocean Science & Technology (Korea, Republic of) and Yonsei Univ. (Korea, Republic of); Joo-Hyung Ryu, Korea Institute of Ocean Science & Technology (Korea, Republic of)

Image mosaic technique is widely used in a field of remote sensing research. However, in case of Geostationary Ocean Color Imager's (GOCI's) mosaic image which is consist of 16 slot images, the radiance level discrepancy was noticed in the cloudy circumstance next to each other slot when acquiring the imagery data in the low Sun elevation angle. We provided, in this study, the in-depth stray light analysis results in order to find out this discrepancy phenomenon, and performed the image restoration with simulated stray light bias.

Stray light analysis as the first step was completed with ray tracing technique based on ASAP program, and we suggested that unwanted radiations from the Earth bright target or the atmosphere such as cloud are major candidates of stray light in the problematic images. For embodying GOCI operational concept, we constructed the Integrated Ray Tracing model consisting of the Sun model as a light source, a target Earth model, and the GOCI optical system model.

In the second step, we investigated the stray light pattern at each slot image including unwanted random source from out of field, and then constructed the simulated mosaic bias image reached at the detector plane. In the simulated bias, the ray path followed the procedures that light travels from the Sun and it is then reflected from the Earth section of roughly 2500km * 2500km in size around the Korea peninsula with 16 slots.

Lastly, we corrected the acquired image with subtracting weighted stray light pattern bias in the third step. The real acquired image was selected UTC-03 image at 16th, October, 2012. In addition, verification was performed to compare the difference among slot boundaries.

8840-6, Session 2

Efficient automatic computation of veiling glare from scatter and ghosts by a simple modification to Monte-Carlo ray tracing

Alan W. Greynolds, Ruda-Cardinal, Inc. (United States)

Veiling glare is a somewhat obsolete term referring to stray light from an in-field extended source bleeding into adjacent dark regions of the image. In most systems ghost reflections and scatter from the contaminated or imperfectly polished optical surfaces are the main culprits. Standard stochastic or deterministic methods for calculating scattered light from out-of-field sources are cumbersome in this domain. On the other hand, basic Monte Carlo ray tracing is straightforward. Its implementation in the GelOE optical engineering software is based on a fast hybrid physical-optics/geometrical-optics technique for surface scatter. However, a prohibitive number of rays are still required to get accurate results. Instead of the standard ray-splitting and importance-sampling modifications to make it more efficient, a much simpler one is proposed and then applied to a representative lens system, resulting in a 100 to 1000 fold reduction in the number of rays required for the same accuracy.

8840-7, Session 2

Revival of the dark core in scattered optical vortices

Salla Gangi Reddy, Ashok Kumar, Shashi Prabhakar, Ravindra P. Singh, Physical Research Lab. (India)

Optical vortices are getting a lot of attention due to their applications in optical manipulation and quantum information. Here, we have experimentally observed the reconstruction of the dark core in scattered optical vortices through the rotating ground glass (RGG) plate. In this, we have generated optical vortices using computer generated hologram and a spatial light modulator. Vortices are passed through the RGG plate and scattered optical vortices are focused with a plano-convex lens of focal length 10cm. The scattered optical vortices do not show a dark core immediately after the RGG plate or the lens. However, the far-field intensity distribution (at focus) of scattered light has a dark core at its center. The diameter and the darkness of core are independent of the speed of the RGG plate i.e. the coherence of scattered light. This has been observed by the line profiles of far-field distributions of scattered vortex with a particular order at different speeds of the RGG plate. A study of the line profiles of scattered vortices of different orders shows that the diameter of the dark core increases with the increase in the order of vortex. These results follow the theoretical results of Mei and Korotkova [Opt. Lett. 38, 91-93]. We have also studied the variation of focal length as a function of distance of the lens from RGG plate. The focal length decreases when lens is moving away from RGG plate.

8840-8, Session 3

Basic approach to define signal-to-noise ratio for adjacent pixels for an uncooled micro-bolometer FPA detector

Ulas Kürüm, Roketsan Missiles Inc. (Turkey)

To define signal and noise values; a passive athermal design (Li, H., Shen, M. 2008. An optically passive athermal infrared optical system. Proc. SPIE Vol 706010.) is used as a basis. Transmission values are calculated accordingly for 10 anti-reflect coated surfaces (dome+4 optics). Range between source object and the optical system is chosen to be 2000 meters and atmospheric attenuation calculated according to NATO literature (STANAG 4347). Optical performance criteria are calculated using computer assisted optical design programs (zemax and code5). Encircled energy values within the areas defined by pixel pitch are extracted from these design outputs to determine the contribution of image to signal as well as to noise. To further define noise, f/# contribution of the design is also considered.

To evaluate the contribution of quality of the optical design to the signal to noise ratio, different alterations of the original optical design are analyzed accordingly.

8840-9, Session 3

Computational methods to compute wavefront error due to aero-optic effects

Victor L. Genberg, Sigmadyne, Inc. (United States); Mark Bury, Keith B. Doyle, Thomas B. Sebastian, MIT Lincoln Lab. (United States)

Aero-optic effects can have deleterious effects on high performance airborne optical sensors that must view through turbulent flow fields created by the aerodynamic effects of windows and domes. Evaluating aero-optic effects early in the program during the design stages allows mitigation strategies and optical system design trades to be performed to optimize system performance. This necessitates a computationally efficient means to evaluate the impact of aero-optic effects such that the resulting dynamic pointing errors and wavefront distortions due to the spatially and temporally varying flow field can be minimized or corrected. To this end, an aero-optic analysis capability was developed within the commercial software SigFit that couples CFD results with optical design tools. SigFit reads the CFD generated density profile using the CGNS file format. OPD maps are then created by converting the three-dimensional density field into a index of refraction field and then integrating along specified paths to compute OPD errors across the optical field. The OPD maps may be evaluated directly against system requirements or imported into commercial optical design software including Zemax® and Code V® for a more detailed assessment of the impact on optical performance from which design trades may be performed.

8840-10, Session 3

Optical design including characteristics of manufactured nanostructures

Christoph A. Wächter, Martin Müller, Erik Förster, Maria Oliva, Dirk Michaelis, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Micro- and nanostructures enable specific optical functionalities which rely on diffractive effects or effective medium features, depending on feature size and wavelength. Any intended functionality of the nanostructure is transferred somehow to its geometric details which can be reasonably straight forward or may require sophisticated numerical modeling when e.g. gratings in the resonance domain are required. Nevertheless, manufactured micro- and nanostructures will deviate from the ideal structure in shape, and material properties might be affected as well. This influences the performance of the optical system wherein these structures will be used. To include such fabrication effects and related tolerances in the system design measured characteristics are most suitable. To this end we use several goniometers where reflection and transmission properties of the artificial structures can be measured as function of input and output angles, wavelength, polarization, and lateral position. Since nanostructures in almost any case are fabricated on planar substrates, the measured characteristics then can be attributed to a planar optical element or surface. The corresponding model of that element which is to be incorporated in a ray-trace engine can be quite simple if diffraction efficiency in a single intended order is considered. Multiple diffraction orders and stray-light effects are required for in depth performance predictions of an optical system including a grating, which presupposes more extensive measurements and a more complex element model, consequently. Implementations relying on several types of nanostructured elements, including arrays of metallic nanoparticles and a metamaterial with asymmetric transmission [1] will be presented.

[1] C. Menzel et al., Phys. Rev. Lett. 104, 253902(2010)

8840-11, Session 4

Analysis of thermally-loaded transmissive optical elements

Gregory J. Michels, Victor L. Genberg, Sigmadyne, Inc. (United States)

The performance metrics of many optical systems are affected by temperature changes in the system through different physical phenomena. Temperature disturbances cause changes in the refractive properties of transmissive optics. Complex distributions of refractive indices that relate to the thermal profile, the thermo-optic refractive index profile, within the optical media can be predicted by the finite element method. One current technique for representing such refractive index profiles is through the generation of OPD maps by integration along integration paths. While computationally efficient, this method has limitations in its ability to represent the effect of the index changes for rays associated with multiple field points and multiple wavelengths. A more complete representation of the thermo-optic refractive index profile may be passed to the optical analysis software through the use of a user defined gradient index material. The interface consists of a dynamic link library (DLL) which supplies indices of refraction to a user defined gradient index lens as ray tracing calculations are being performed. The DLL obtains its refractive index description from a database derived from the thermal analysis of the optics. This process allows optical analysis software to perform accurate ray tracing for an arbitrary refractive index profile induced by changes in temperature. This paper is an update to this work already started in SPIE conference proceedings paper 8127-19.

8840-12, Session 4

STOP analysis modeling and the cielo solution platform

Mike Chainyk, Eric J. Cady, Daniel B. Klein, Gregory J. Moore, Stuart Shaklan, Luis Marchen, Marie Levine-West, Jet Propulsion Lab. (United States)

The Cielo software platform provides a solution capability for addressing high fidelity tightly coupled thermal, structural and optical (STOP) system design and performance modeling. The tenor of the approach lies in creation of a single instruction file that is, of itself, archival in its description of the finite element analogue to the true geometry through element topology, material property and optical surface specifications. Environmental characterization requires that we include the complete set of static as well as dynamic physical parameters that define the loads, boundary conditions and constraints across all three disciplines. Generally, the cascading effects (bucket brigade) are resolved automatically in a single analysis submittal as Cielo computes temperature, strain, displacement, rigid body optical surface motions and local deformation optical aberrations. Various optical metrics can be resolved with a simple call from within Cielo to either commercial or customized routines that post-process quantities such as WFE, beam walk and contrast.

The activity being described here will focus on the methodology for creating the single multidisciplinary model of interest and complete specification of the problem. Commercial modeling software will be discussed with respect to their capacity for creating the input constructs

upon which Cielo is driven. Given the breath of the Cielo solution, no commercial modeling package provides complete input descriptor coverage and we discuss efficient procedures for stop gap resolution. A number of intermediate solution metrics will be described with respect to measuring solution quality and the general problem flow and engineering principles employed will be examined. An end to end integrated physics model will provide the basis for a Cielo model building exercise and solution demonstration.

8840-13, Session 4

Coupling commercial software for STOP analysis at MIT Lincoln Laboratory

Gerhard P. Stoeckel, Keith B. Doyle, MIT Lincoln Lab. (United States)

Integrated optomechanical modeling provides critical insights into the interdisciplinary behavior and dynamics of high performance optical systems operating in ground, air, and space environments. Integrated models serve as predictive test beds capturing complex environmental conditions and concurrent disturbances yielding deterministic performance predictions at any point in time. MIT Lincoln Laboratory is developing custom software comprising an enterprise framework for use during the design and testing stages of hardware programs that couples existing commercial thermal (ThermalDesktop), structural (Nastran), optical (Zemax), and control (Matlab) software tools to inform architecture and system design decisions. Initial efforts have focused on development of a feature-rich software package designed to simplify STOP (structural-thermal-optical performance) analysis without sacrificing functionality or flexibility. This paper discusses the design of a framework and user interface for simple setup, execution and validation of STOP analyses on arbitrarily complex optical systems.

8840-15, Session 4

Multiphysics modeling and uncertainty quantification for an active composite reflector

Lee D. Peterson, S. Case Bradford, John E. Schiermeier, Gregory S. Agnes, Scott A. Basinger, Jet Propulsion Lab. (United States)

A multiphysics, high resolution simulation of an actively controlled, composite reflector panel is developed to extrapolate from ground test results to flight performance. The subject test article has previously demonstrated sub-micron corrected shape in a controlled laboratory thermal load. This paper develops a model of the on-orbit performance of the panel under realistic thermal loads, with an active heater control system, and performs an uncertainty quantification of the predicted response. The primary contribution of this paper is the first reported application of the Sandia developed Sierra mechanics simulation tools to a spacecraft multiphysics simulation of a closed-loop system. The simulation was developed so as to have sufficient resolution to capture the residual panel shape error that remains after the thermal and mechanical control loops are closed. As such, the thermal mesh is converged to milli-kelvin scale resolution, and the structural mesh is converged to submicron scale resolution, both over millimeters of spatial wavelengths. An uncertainty quantification analysis was performed to assess the predicted tolerance in the closed-loop wavefront error. Key tools used for the uncertainty quantification are also described.

8840-16, Session 4

The diffraction grating in the Ivory optomechanical modeling tools

Alson E. Hatheway, Alson E. Hatheway Inc. (United States)

In imaging spectrometers it is important that both the image of the far-field object and the image of the spectra be stable on the detector plane. Lenses and mirrors contribute to the motions of these images but motions of the diffraction grating also have their own influences on these image motions. This paper develops the vector equations for the images (spectra) of the diffraction grating and derives their optomechanical influence coefficients from them. The Ivory Optomechanical Modeling Tools integrates the diffraction grating into the larger optical imaging system and formats the whole system?s influence coefficients suitably for both spreadsheet and finite element analysis methods. Their application is illustrated in an example of a spectrometer exposed to both static and dynamic disturbances.

8840-17, Session 4

Multidisciplinary model-based-engineering for laser weapon systems

Stephen C. Coy, Timelike Systems LLC (United States)

No Abstract Available

8840-18, Session 5

A method for measuring laser incident direction with non-imaging mode and resolution analysis

Bing Li, Yuejin Zhao, Xiaohu Guo, Jingshui Zhang, Lingqin Kong, Beijing Institute of Technology (China)

One of the most crucial techniques of laser warning system is to acquire the direction information from the laser threat. According to the low resolution of laser warning system with imaging mode, a new method for measuring laser incident direction which possessed higher resolution was proposed. This novel method was based on cylindrical lens group and linear IRFPA, and the laser incident direction was achieved by offset of line spot. It not only deduced the direction formulas, but also analyzed the resolution of measuring laser incident direction in detail. The simulation result shows that the FOV of this new kind of laser warning system could achieve ±16°; the azimuth resolution is up to 0.52° and pitch resolution is up to 0.017°; the resolution increases with incident angle. In addition, an experiment with visible light, single cylindrical Len, linear array CCD was done to verify this method and its advantage on resolution. The analysis of laser incident orientation resolution is significant to select suitable parameter of detector and demonstrate orientation resolution of system.

8840-19, Session 5

Feasibility of near-infrared markers for guiding surgical robots

Azad Shademan, Matthieu F. Dumont, Simon Leonard, Axel Krieger, Peter C. W. Kim M.D., Children’s National Medical Ctr. (United States)

Automating surgery using robots requires robust visual tracking. The surgical field has often poor light conditions where several organs have similar visual appearances. In addition, the field of view might be occluded by blood or tissue. In this paper, the feasibility of near-infrared (NIR) fluorescent imaging for vision-based robot control is studied. The NIR region of the spectrum has several useful properties including deeper depth penetration. We study the optical properties of a clinically-approved NIR fluorescent dye, indocyanine green (ICG), with different concentrations and quantify image positioning error of ICG marker when occluded by artificial tissue.

8840-20, Session 5

Integrated analysis of FORMOSAT-5 remote sensing instrument in space

Chia-Ray Chen, Ching-Wei Chen, Mei-Yi Yang, Cheng-En Ho, National Space Organization (Taiwan); Shenq-Tsong Chang, Ting-Ming Huang, Instrument Technology Research Ctr. (Taiwan)

FORMOSAT-5 is the first space program fully developed by National Space Organization (NSPO). The Remote Sensing Instrument (RSI) will provide spatial resolution of 2 meters in panchromatic band and 4 meters in multi-spectral bands. The optical system is composed of two reflective aspheric mirrors and spherical corrector lens set. CFRP structure is used for the optomechanical system to reduce mass. Although the telescope system can be well aligned on ground, the space thermal environment can result in thermal distortion of telescope system and impact the final image quality. Flight predictions of FORMOSAT-5 RSI were done to get the quantitative thermal distortion of mirrors and structural system. The system optical performance, i.e. MTF, was also derived by the optical model with the input from thermal distortion results, i.e. Zernike polynomials. RSI performance in space is location-dependent. Detailed analysis results and discussions will be revealed in this paper.

8840-21, Session 5

Measurement in the fringes: Experimental mechanics approaches for model verification of precision structures

Gregory S. Agnes, Samuel Case Bradford, Lee D. Peterson, Jet Propulsion Lab. (United States)

No Abstract Available

Sunday - Tuesday 25–27 August 2013

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8841-1, Session 1

Simultaneous color-mixing and collimation within LED package *(Invited Paper)*

Ivan Moreno, Jose Carlos Basilio, Univ. Autónoma de Zacatecas (Mexico)

A compact encapsulating lens is proposed and analyzed, which simultaneously collimates and mixes the tunable light from red, green and blue (RGB) light-emitting diode (LED) chips. Colored LED chips are embedded within a spherical lens, and a section of the sphere that surrounds chips is mirrored with a diffuse reflector. Color light is mixed by multiple total internal reflections (TIRs), the scattering mirror breaks TIR, and light escapes only in a narrow beam in the forward direction. The color uniformity, the beam pattern, and efficiency are analyzed by Monte Carlo ray tracing calculations.

8841-2, Session 1

Optical design for anti-glare LED projection based on a confocal double-reflector

Yi-Chien Lo, Xuan Hao Lee, Chih-Chi Tsai, Wei-Ting Chien, Ching-Cherng Sun, National Central Univ. (Taiwan)

In this paper, we present a new optical design of a confocal double-reflector for white LED light. It can perform uniform illumination with a specific projection angle. Furthermore, our design can prevents direct view of the LED, and the measured veiling luminance is much lower than that in general LED-based projection lamps.

8841-3, Session 1

Optical design of the projection lamp for large area based on white LEDs

Jhih-You Cai, Yi-Chien Lo, Jheng-Yu Cai, Ching-Cherng Sun, National Central Univ. (Taiwan)

In our research, we designed a projection lamp for large area based on white-light LEDs. In general, the projection lamp of the outdoor lighting was set up in the margin of the target area. However, most of the projection lamps of the outdoor lighting were distortion light pattern instead of specific light pattern, e.g., rectangular light pattern. This means that the specific light pattern was illuminated in the target area and the energy was saved. In design of the projection lamp, we first built a precise optical model for the high-power LED produced by CREE in mid-field verification to guarantee the accuracy of our simulation. After creating the precise light source model, we designed the process of the secondary optics of projection lamp. Since the projection lamp had tilted angle and set up in the margin of illumination area, to perform uniform and rectangular light pattern was not easy. When the angle of the lamp did not tilt, the shape of the light pattern was trapezoid. When the lamp had tilted angle, the shape of the light pattern became rectangle. This concept was correcting the shape of light pattern and illuminating for large area, when the projection lamp had tilted angle and set up in the margin of illumination area.

8841-4, Session 1

Hybrid solid state illuminator

Junejei Huang, YuChang Wang, Delta Electronics, Inc. (Taiwan)

A laser-phosphor projector uses laser to pump phosphors and applies the excited lights as projecting light source for full color display. Conventionally, red color in laser-phosphor projector is not sufficient and size of the laser-phosphor light module is too large to fit into the existing optical engine that originally designed for the UHP lamp. To overcome the difficulties of the conventional laser-phosphor illuminator, a hybrid solid state illuminator is proposed.

In this hybrid solid state light source, blue and red lights from laser diodes and yellow light from YAG phosphor are combined and formed into a compact lamp module. 100 sets of laser diodes (with collimating lens in front of each) are concentrated and aligned by stripes of mirrors and formed into a laser bank. The assembly technique, coupling efficiency, spot size and beam quality of the laser bank are discussed.

Laser light of 445nm is guided and converged into the phosphor disk. For the phosphor, the material choice, its binder and Al disk that supporting and ventilating the phosphor are discussed.

Yellow spectrum and residual blue light are generated after the pumping of the 445nm blue laser light. The generated light is further combined with laser lights of 462nm and 639nm by using a structure comprising TIR prism and narrow band reflection filter. A wide color gamut (Rec. 709) and high efficiency are got. Using this hybrid solid state lamp module in a 3-chip projector having 0.95" DMD, an output of 10K lumen to the screen will be demonstrated.

8841-5, Session 2

Offer more different wavelength bands for plant cultivation using a polygonal beam splitter

Yi-Shiuan Chen, Jong-Woei A. Whang, National Taiwan Univ. of Science and Technology (Taiwan)

More and more developed countries in the world advocate the importance of natural and sustainable green life. As the residents of the global village, we need to have the consciousness of environmental protection. The Shanghai World Expo 2010 Exhibition and the 2010 Taipei International Flora Exposition both have demonstrated a lot of landscape plants and green buildings. The United States, China and Taiwan have been concentrated on the development of plant cultivation which needs proper light source for high economic crops and flowers. Therefore, in accordance with the characteristics of plants we supply the lighting illuminations in different wavelength band for plants growth.

In our research, we design a polygonal beam splitter. Usually beam splitters separate the primary colors of light into red, blue and green lights, but this polygonal beam splitter split sunlight by using the coating method which the outer and the inner of the dichroic mirror are coated with different optical films. The polygonal beam splitter can separate sunlight into more different light wavelengths with delicate color temperature, offering more different wavelength bands for plant cultivation.

8841-6, Session 2

Radiance limits of ceramic phosphors under high excitation fluxes

Alan Lenef, John Kelso, Yi Zheng, Maxim Tchoul, OSRAM SYLVANIA Inc. (United States)

Thermodynamic arguments suggest that the radiance of a luminescent spot can exceed the radiance of its shorter wavelength incoming pump source. In practice, however, thermal quenching and optical saturation (non-thermal) limit the maximum attainable radiance. We present experimental data from static laser-pumped Ce:YAG and Ce:GdYAG ceramics in which both of these limits have been investigated. Optical pumping intensities exceeding 100W/mm2 have been shown to produce only modest efficiency depreciation due to optical saturation at low overall pump powers because of the short Ce3+ lifetime. However, when pump powers reach a few watts, heat-transfer bottlenecks within the ceramic and interfaces severely limit maximum pump intensities. We find that surface temperatures of laser-pumped ceramics can easily exceed 150 °C, causing considerable thermal-quenching losses. We also find that in some cases, the loss of quantum efficiency with increasing temperature can cause a thermal run-away effect, resulting in a rapid loss in converted light and sample over-heating. While one can still obtain radiant emittances on the order of several W/mm2, these temperature quenching effects ultimately limit converted light radiance. Finally, we use diffusion-approximation radiation transport models to simulate some of these nonlinear heating effects in high-scattering ceramics and compare with experimental data.

8841-7, Session 2

Beam shaping for high-uniformity illumination based on power chip LEDs

Rodolfo Garcia-Camacho, Jhe-Syuan Lin, Soo-Fan Phua, Yi-Chien Lo, Ching-Cherng Sun, Chao-Wen Liang, National Central Univ. (Taiwan)

Uniform illumination is a prerequisite in many optical systems. However, light sources usually don't produce enough uniformity. Therefore, some modification of the irradiance pattern produced by the light source is needed. In this paper, we design an optical system with fly's eye lens to redistribute light from an LED source and obtain high uniformity illumination and efficiency. Our work also includes designing a collimating system and doing a complete analysis. Finally, we demonstrate our design by testing a real optical system

8841-8, Session 2

Application of heterogeneous microlenses for solid state lighting

Weiting Shih, National Taiwan Univ. (Taiwan)

In recent years, LED was applied to lighting in bulk, mostly used in territory of backlight lighting. Therefore, our research would focus on backlight lighting. In this paper, two methods were adopted to obtain freeform surface with axial symmetry and non-axial symmetry. Then by the freeform lens constructed by us, we would make the light field intensity more uniform. In the end of the thesis, we would utilize MLA to approximate the shape of the freeform lens, and adjust the curvature radius and size of the micro lens, and the arrangement way of the micro lens by the simulation results. Through repeated trials, we would achieve the uniformity effect of LED's light.

8841-9, Session 3

Analysis of the correction properties and capabilities of optical systems

Sergey N. Bezdidko, Open Joint-Stock Co. (Russian Federation); Yuri A. Roy, Open Joint-Stock Co. (Russian Federation)

The unique properties of orthogonal aberrations provide an opportunity to form a system of criteria and methodology for evaluating correction properties and capabilities of optical systems based on the use of the expansion of the wave aberration in generalized Zernike polynomials in the three-dimensional domain of field - pupil $0 \leq r \leq 1$, $0 \leq \rho \leq 1$, $0 \leq \varphi \leq 2\pi$ and the separation of the contributions of aberrations of lower and higher orders in the image deterioration.

This report describes practical application of proposed approaches in analysis and optimization and examples of calculation of the specific optical systems.

8841-10, Session 3

Orthogonal aberrations and their role in lens design

Sergey N. Bezdidko, Open Joint-Stock Co. (Russian Federation)

The author introduces a complete set of polynomials that are orthogonal to the three-dimensional region (generalized Zernike polynomials). These polynomials make it possible to obtain orthogonal expansion of the wave aberration in the three-dimensional domain of field - pupil $0 \leq r \leq 1$, $0 \leq \rho \leq 1$, $0 \leq \varphi \leq 2\pi$. These permit to determine the orthogonal system of individual aberrations and introduce a classification of individual aberrations depending on the degree of field and pupil variables r ρ, φ. The author shows that orthogonal aberrations have a number of unique properties which makes it possible to build new effective approaches and techniques to the design of optical systems.

The developed approach describing the aberration properties of optical systems by means of orthogonal aberrations and its use in the construction of new methods and techniques to the design of optical systems form a new section of lens design, namely, "The theory of orthogonal aberrations and its applications in the design of optical systems."

8841-11, Session 3

Polarization fields for understanding polarization aberrations in imaging systems *(Invited Paper)*

José Sasián, College of Optical Sciences, The Univ. of Arizona (United States)

Polarization effects in imaging systems can be significant and, therefore, understanding the subject of polarization aberrations is important in the design of optical instruments. However, and despite a few works on the subject of polarization aberrations, it is still not clear how best to approach learning of this subject, and thus acquire a solid foundation.

This talk provides a foundation to easily understand polarization aberrations in optical imaging systems by developing the concept of polarization fields. A useful set of fields is constructed, notably from the aberration function of plane symmetric systems, and used to get insight. We also discuss polarization aberration coefficients and provide some insightful examples. The audience will get a useful primer on the topic.

8841-12, Session 3

Design of fisheye lens with slope-constrained Forbes aspheres

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1. Introduction

In the information age nowadays, fisheye lenses are more and more widely used in navigation, surveillance, machine vision, etc. [1-4]. Aspheric surfaces are often used in their designs in order to meet the requirements on image quality and system size and weight. A new method of specifying aspheric surfaces was proposed by G. Forbes [5], which has significant advantages in the design of rotational symmetry systems [6-7]. Now Forbes asphere has been integrated into the optical design software CODE V [8].

2. Technical specifications of the fisheye lenses and design considerations

Because of the very large field angle, a fisheye lens for automobile navigation must have a large numerical aperture in order to provide sufficient illumination at the edge of the image surface. At the same time, strict restrictions on the lens element number and system overall length greatly increases the difficulty of the design task.

The main specifications for our design are as follows: diagonal size of the detector = 1/4"; full field angle ≥ 180°; F/number ≤ 2.5; system length ≤ 30mm; full field relative illumination ≥ 40%; Number of lens elements ≤ 6.

The material of the first lens element has to be glass in order to sustain the sometimes harsh environmental conditions outside the vehicle. The materials of the lens elements with aspheric surfaces need to be plastic (APEL) so that these elements can be molded in mass production to reduce the cost. For these molded lens elements, both surfaces can be aspheric since there is not much difference in cost. Forbes asphere is used to describe their surface shapes, so that the surface slopes can be effectively constrained during the optimization to be suitable for molding.

3. Design results and analysis

Two design results are given. Figure 1 and figure 2 show their system layouts, MTF curves and curves of field curvature and distortion. The first design gives a full field angle of 190°. It is very compact, with an overall length of only 14.3mm and four lens elements, including two aspheric elements. The MTF values for almost all the sampled fields are above 0.4 at the Nyquist frequency of 45lp/mm, the f-θ distortion is less than 10%, and the full field relative illumination is greater than 40%.

The second design provides an even larger field angle of 210°. Six lens elements are used in this design, again with two aspheric elements. The overall length of this design is 30mm, which is still more compact than most common fisheye lenses. The MTF values remain greater than 0.4 except for a couple of sampled fields at the corner of the image surface. The f-θ distortion is further reduced to 2%, and the full field relative illumination is again greater than 0.4.

4. Conclusions

In this Paper, two fisheye lenses are designed with super field angle 190º and 230º respectively, the results of the designs show that Forbes aspheres can not only improve the image quality but also decrease the difficulties of the fabrication and testing of aspheric surface.

8841-13, Session 3

Analytic formulas of the aspheric terms for Convex-Plano and Plano-Convex aspheric lenses

Maximino M. Avendaño-Alejo, Univ. Nacional Autónoma de México (Mexico)

The aspheric lens can help simplify optical system design by minimizing the number of elements required and yields sharper images than conventional lenses. In this work we provide analytic formulas for fews aspheric terms either Plano-Convex or Convex-Plano aspheric lenses. These formulas are obtained considering a expansion in Taylor's series from exact caustic equation produced by aspheric lenses. A comparison between our aspherical terms obtained through these formulas and the aspheric terms provided by another methods of design are presented, showing a well agreement in order to reduce the spherical aberration.

8841-14, Session 4

Multi-core and GPU accelerated simulation of a radial “star” target imaged with equivalent t-number circular and Gaussian pupils

Alan W. Greynolds, Ruda-Cardinal, Inc. (United States)

Results from the GelOE optical engineering software are presented for the through-focus, monochromatic coherent and polychromatic incoherent imaging of a radial “star” target for equivalent t-number circular and Gaussian pupils. The FFT-based simulations are carried out using OpenMP on a multi-core desktop computer, with and without the aid of a many-core NVIDIA GPU accessing its cuFFT library. It is found that a custom FFT optimized for the 12-core host has similar performance to a simply implemented 256-core GPU FFT. A more sophisticated 448-core GPU version (tuned to reduce overhead) is 20 to 28 times faster than a basic FFT implementation running on one CPU core.

8841-15, Session 4

Man versus machine: a lens design challenge *(Invited Paper)*

Donald C. Dilworth, Optical Systems Design, Inc. (United States); David R. Shafer, David Shafer Optical Design (United States)

After a generation of writing and improving lens design software, it is time to assess where we are. Specifically, can a modern program compete, or surpass, the best human designers? Here we describe a friendly contest between two leaders in the field.

8841-16, Session 4

Design of wearable binoculars with on-demand zoom

Robert R. Boye, Ronald S. Goeke, Jeffrey P. Hunt, Aaron M. Ison, Bradley H. Jared, Jamin R. Pillars, Michael P. Saavedra, William C. Sweatt, W. Graham Yelton, Edward G. Winrow, Steven L. Wolfley, Sandia National Labs. (United States)

Sandia has developed an optical design for wearable binoculars utilizing freeform surfaces and switchable mirrors. The goals of the effort included a design lightweight enough to be worn by the user while providing a useful field of view and magnification as well as non-mechanical switching between normal and zoomed vision. Sandia's approach is a four mirror, off-axis system taking advantage of the weight savings and chromatic performance of a reflective system. The system incorporates an electrochromic mirror on the final surface before the eye allowing the user to switch between viewing modes. Results from a prototype of a monocular version of an 6.6x design will be presented. The individual mirrors, including three off-axis aspheres and one true freeform, were fabricated using a diamond-turning based process. A slow-slide servo process was used for the freeform element. Surface roughness and form measurement of the freeform mirror will be presented as well as the expected impact on performance. The alignment and assembly procedure will be reviewed as well as the measured optical performance of the prototype. In parallel to the optical design work, development of an electrochromic mirror has provided a working device with faster switching than current state of the art. Switchable absorbers have been demonstrated with switching times less than 0.5 seconds. The deposition process and characterization of these devices will be presented. Finally, details of an updated optical design with additional freeform surfaces will be presented as well as plans for integrating the electrochromic mirror into the system.

8841-17, Session 4

Optical design and optimization of zoom optics with intermediate image

Yi-Chin Fang, National Kaohsiung First Univ. of Science and Technology (Taiwan)

An optical design of 9X optical miniature zoom lens with intermediate image method has been presented in this research. Intermediate image is applied in order to minimize of front diameter of zoom optics. Moreover, a compensative optimization method with assistance of Genetic Algorism is introduced in this research with a new concept of DLGS,(Discrete

Lens Groups Shifts) which not only solve the complicated problem of intermediate image itself but also improve the performance of optics. Genetic algorithms (GA) written in CODE V plays the role at finding out the appropriate parameters such as curvatures, thicknesses, glass materials and etc. Besides, one table with great lens groups shifts by GA would be created to move the lens groups on the optimal positions of different zooms. As a result, the DLGS optimization method associated with the GA optimization eliminate the zoom lens diameter averagely 25% better than traditional ones.

8841-18, Session 4

A 3D photographic capsule endoscope system with full field of view

Wei-De Jeng, Yi-Chinn Kung, Kuan-Heng Tao, Ou-Yang Mang, National Chiao Tung Univ. (Taiwan)

Current capsule endoscope uses one camera to capture the surface image in the intestine. It can only observe the abnormal point, but can not know the exact information of this abnormal point. Using two cameras can generate 3D images, but the visual plane changes while capsule endoscope rotates. It causes that two cameras can't capture the images information completely. To solve this question, this research provides a new kind of capsule endoscope to capture 3D images, which is "A 3D photographic capsule endoscope system ". The system uses three cameras to capture images in real time. The advantage is increasing the viewing range up to 2.99 times respect to the two camera system. The system can accompany 3D monitor provides the exact information of symptom points, helping doctors diagnose the disease.

8841-19, Session 5

Double micro-prism array design for reducing dispersion on prism-based stereo camera system

Wen-Shing Sun, Pu-Yi Chu, National Central Univ. (Taiwan)

In this study, we used the two micro-prism array to reduce the chromatic aberration of the system in the stereo photography. First of all, we select two partial dispersion differences smallest difference with the Abbe number of plastics as the material of the micro-prism array, we think this can eliminate the primary chromatic aberration, while secondary chromatic aberration will be smaller. In order to divide the image into two, we determine the total deviation angle, and then find the vertex angle combination which makes the primary chromatic aberration is close to zero. Finally, we use optical software to compare the results of single and double micro-prism array.

8841-20, Session 5

Micro-optical elements for optical wireless applications

Xian Jin, Daniel Guerrero, Richard Klukas, Jonathan F. Holzman, UBC Okanagan (Canada)

Optical wireless technology is an attractive solution for indoor wireless networks seeking high-bandwidth and mobility. Developments have emerged for improved signal reception in optical wireless communication (OWC) and optical wireless location (OWL) applications, and imaging receivers are often employed in these systems. Imaging receivers use lenses and arrayed photodetectors to image an overhead optical transmitter grid and isolate the individual optical channels. The contemporary challenges for these implementations relate to the desire for a wide field-of-view (FOV) with an integrated architecture. The wide FOV can establish links with multiple optical wireless channels, but this capability is difficult to integrate in micro-optical architectures.

In this work, customized microlenses are introduced for use in OWC and OWL applications. The microlenses are fabricated with especially high contact angles to establish large numerical apertures (NAs) and wide FOVs. An electro-dispensing technique is used to create the microlenses. Each microlens is formed from dispensed UV-curable polymer with pressure-control defining the microlens volume. At the same time, a tunable voltage is applied to the metal dispensing tip to fine-tune the microlens profile by way of the electrowetting effect. When the ideal microlens profile is achieved, UV-curing is applied. This technique is used to create microlenses with diameters down to 200 μm and NAs up to 0.6. The microlenses are integrated above a CMOS imaging sensor for operation with especially wide FOVs. The prospects for these new micro-optical elements are discussed for emerging OWC and OWL applications.

8841-22, Session 5

Optical architecture of the new generation Infrared Atmospheric Sounder Interferometer (IASI-NG)

Clement Luitot, Ctr. National d'Études Spatiales (France)

IASI (Infrared Atmospheric Sounder Interferometer) is a Fourier Transform Spectrometer (FTS) working in the 3,6μm – 15,5μm range, dedicated to Numerical Weather Prediction, atmospheric chemistry and climate monitoring. The second flight model (2 out of 3) is now in orbit and operational, as a payload of the MetOp-B satellite.

A new generation of instrument (IASI-NG) to continue the IASI mission with increased performances is currently investigated by the French Space Agency (CNES). The performance objective is mainly a spectral resolution and a radiometric noise divided by two compared with the IASI ones. Many different concepts of FTS were studied to try to fulfill these challenging requirements.

This paper presents the different envisaged optical architecture and associated trade off.

The major issue of the concept is to manage the so-called self-apodization of the interferogram and the associated degradation of the spectral resolution induced by the wider Field of View and the longer Optical Path Difference. Increasing these two quantities have very constraining consequences on the optical architecture. Another critical point is the control of strayligth which is quite severe and which has been taken into account early in the optical design. To assess the performances of the interferometer, different optical models were built combining analytical approach with ray tracing technics. We will describe the impacts of the demanding spectral requirements on the optical components and our analyses, based on these models will be presented.

8841-23, Session 5

A three-channel miniaturized optical system for multi-resolution imaging

Gebirie Yizengaw Belay, Heidi Ottevaere, Youri Meuret, Hugo Thienpont, Vrije Univ. Brussel (Belgium)

Multi-channel imaging systems are inspired by natural compound eyes of insects. Such systems have many channels that share the total Field-Of-View (FOV). In this work, our aim was to manipulate the different channels such that different imaging properties (focal length, angular resolution) are obtained for each channel. This adds multi-resolution functionality to the imaging system. We have designed a three-channel imaging system where the first channel has the highest angular resolution (0.0096 degree) and narrowest FOV (7 degree) and the third channel has the smallest angular resolution (0.078 degree) and widest FOV (80 degree). The second channel has intermediate properties. Each channel consists of 4 aspherical lens surfaces and an absorbing baffle that avoids crosstalk with the neighbouring channels. The aspherical lens surfaces have been fabricated in PMMA by ultra-precision diamond turning and the baffles by metal additive manufacturing. The integrated and stacked imaging system comprises two lens plates featuring the 4 lens surfaces, an absorbing plate with baffles, all connected by thin capillary columns running through alignment holes, and a commercial CMOS sensor. The CMOS sensor simultaneously captures images of different resolution at its different segments. This creates a possibility of implementing different image processing algorithms on the different image sensor segments. The MTF and FOV of the channels were calculated from the captured images. The obtained results show that there is a good agreement between the performances of the simulation and the experiment and this paves the way towards miniaturized smart imaging systems.

8841-24, Session 6

Internal structure of bokeh image in camera lenses with aspheric surfaces

Viktor P. Sivokon, Mike Thorpe, Raytheon ELCAN Optical Technologies (Canada)

In photography, bokeh is the characteristic of the image of out-of-focus points of light as rendered by a particular lens and is sometimes treated as a lens performance metric. We present theoretical, numerical and experimental analysis of the internal structure of bokeh images as seen in shots taken with camera lenses which incorporate aspheric surfaces. We show that detailed structure of bokeh closely reflects characteristics of the manufacturing process for aspheric surfaces, and is due to light diffraction on the phase grating associated with the surface. We derive a simple formula for estimating intensity modulation ratio of the resulting bokeh based on the out-of-focus distance, amplitude and frequency of surface profile undulations. Numerical simulations of bokeh formation were carried out for two imaging systems: a simplified parabolic mirror and a photographic lens. The simplicity of the parabolic imager allows for direct comparison between theory and simulation. We find that modulation depth in the bokeh structure calculated by light propagation based simulation agrees with theory when the modulation depth is < 30%. Bokeh is found to be highly sensitive to the presence of residual aspheric surface structures. Even when peak to valley departures of these structures are reduced to such low levels that that there is negligible impact on the modulation transfer function, structure and modulation depth in the bokeh may still be quite pronounced. Finally, bokeh obtained for a built lens with known residual aspheric surface structure is shown to be in agreement with a numerical simulation of the imagery.

8841-25, Session 6

Some methods of determination of limit potential image quality of optical systems of various complexities using database of optical systems

Sergey N. Bezdidko, Open Joint-Stock Co. (Russian Federation)

In the report some methods of processing of the information contained in a database of the optical systems are offered with the purpose of extraction of the knowledge, the experience and the intuition of the designers, coded in the database.

Statistical analysis of external characteristics (angular field of view, aperture, focal length), the structural characteristics (number of lenses, etc.) and achieved aberration correction of optical systems has revealed important relationships between characteristics. This allows us to develop methods of analysis of the maximum possible image quality of optical systems of various complexities.

8841-26, Session 6

Stray light analysis of active laser ranging optical system

Jinsuk Hong, Samsung Thales Co., Ltd. (Korea, Republic of)

We performed the stray light analysis of the Active Laser ranging system. To analyze the system, optical components and mechanical components were imported to ASAP software. Actual measurement data of the coating and ASAP's inner library of scatter properties were applied to the optical components. Mechanical components were considered to be 100% absorbing media in this simulation to simulate the optical components effect only.

First, we check the backward reflection to the FPA array caused by the wedge scanner. Since the wedge scanner rotates in different speed, we selected specific position of each scanner and performed the analysis. We can conclude that Scanner rotation position doesn't affect the performance of the FPA.

Then, we check the inner reflection caused by the optical components such as ghost effect. Ray tracing was performed in three fields, center, 0..7 and corner, and we found the Filter's ghost effect can be problem. To eliminate the ghost from the filter, we rotated the filter. We can confirm the Signal-to-Noise ratio were improved by simulation and examination.

8841-34, Session PMon

Parametric analysis of the effect of scatter upon the modulation transfer function

James E. Harvey, Richard N. Pfisterer, Scott Ellis, Photon Engineering LLC (United States)

The modulation transfer function (MTF) is widely used as the image quality criterion of choice for imaging applications where fine detail in extended images needs to be specified or evaluated. This is particularly true for imaging systems degraded by diffraction effects and geometrical aberrations. However, there seems to be a perception among many optical engineers that the MTF is not significantly degraded by scattered or stray light. This perception may be due to the fact that wide-angle scattered light does not visibly distort the fringes of a full-aperture test interferogram. In this paper we present a detailed parametric analysis of the effect of scattered light upon the MTF of an imaging system, and illustrate the results for three specific applications: (i) a short-wavelength extreme ultraviolet Newtonian telescope where scattering effects can dominate both diffraction effects and aberrations in the resulting image degradation, (ii) a visible Newtonian telescope with state-of-the-art optical surfaces which produce no significant effect upon the MTF, and (iii) a system made up of three diamond-turned off-axis aspheric mirrors where we use the predicted MTF to estimate whether post-polishing will be required to meet a specific image quality requirement. We also discuss how to calculate the MTF degradation due to stray light from bulk or particulate scatter provided either measured or assumed BSDF data is available.

8841-35, Session PMon

Innovative wide-field and fast Schmidt camera design

Sandrine Pascal, Sébastien Vivès, Observatoire Astronomique de Marseille-Provence (France); Robert Barkhouser, Johns Hopkins Univ. (United States)

It is commonly accepted that Schmidt cameras allow achieving fast F-ratio and large field of view. Developed from the 1930s, the classical Schmidt cameras are made of full-aperture lens corrector located at the center of curvature of a spherical mirror. The combination of these two elements produces a system free of the four primary aberrations (spherical, coma, astigmatism and distortion). Only the field curvature

remains but it can be compensated by the use of a field flattener (before the focal plane).

In the framework of the SuMIRe Prime Focus Spectrograph (PFS) being developed for the 8-m class SUBARU telescope, we are proposing an innovative Schmidt camera observing a large field-of-view (20 degrees in diameter) with a very fast beam (F/1). Basically, we introduced a catadioptric mirror (i.e. a meniscus with the reflection on its back surface, like a Mangin mirror), instead of the classical spherical mirror.

In this paper, we will describe in detail the proposed optical solution for SuMIRe/PFS and the performance achieved. We will also present a parametric analysis of our solution allowing outlining the advantages and limitations of our approach for other applications.

8841-36, Session PMon

Pyramid wavefront sensor for image quality evaluation of optical system

Dan Zhou, Zhendong Chen, Shanghai Astronomical Observatory (China)

When the pyramid wavefront sensor is used to evaluate the imaging quality, placed at the focal plane of the aberrated optical system e.g., a telescope, it splits the light into four beams. Four images of the pupil are created on the detector and the detection signals of the pyramid wavefront sensor are calculated with these four intensity patterns, providing information on the derivatives of the aberrated wavefront. Based on the theory of the pyramid wavefront sensor, we are going to develop simulation software and a wavefront detector which can be used to test the imaging quality of the telescope. In our system, the subpupil image intensity through the pyramid sensor is calculated to obtain the aberration of wavefront where the piston, tilt, defocus, spherical, coma, astigmatism and other high level aberrations are separately represented by Zernike polynomials. The imaging quality of the optical system is then evaluated by the subsequent wavefront reconstruction. The performance of our system is to be checked by comparing with the measurements carried out using Puntino wavefront instrument (the method of SH wavefront sensor). Within this framework, the measurement precision of pyramid sensor will be discussed as well through detailed experiments. In general, this project would be very helpful both in our understanding of the principle of the wavefront reconstruction and its future technical applications. So far, we have produced the pyramid and established the laboratory setup of the image quality detecting system based on this wavefront sensor. Preliminary results are obtained, in that we have obtained the intensity images of the four pupils. Additional work is needed to analyze the characteristics of the pyramid wavefront sensor.

8841-37, Session PMon

Freeform mirror polishing for compensation on non-symmetry system aberrations of remote sensing instrument

Ching-Hsiang Kuo, Zong-Ru Yu, Cheng-Fang Ho, Wei-Yao Hsu, Fong-Zhi Chen, Instrument Technology Research Ctr. (Taiwan)

Cassegrain optical systems are widely used in remote sensing instrument. Cassegrain telescope is composed of a primary mirror (M1), a secondary mirror (M2), and a set of correction lenses. The system aberrations of telescope could be corrected and balanced by M1 and M2. In the event of deformation of telescope assembly, the non-symmetry aberrations will be induced to the optical system and reduce the optical performance. The non-symmetry aberrations could be measured after completing of M1 and M2 assembly and alignment processes. We could compensate this identified error to M1 or M2 for improving the optical performance. The error compensation on M2 is efficient for polishing process due to the smaller aperture. In this study, we apply an exact aberration that was caused by deformation of mirror supporting and gravity on the designed aspheric surface of M2. The surface of M2 becomes freeform from aspheric. The polishing process combines the techniques of conventional lapping and CNC polishing. We apply the conventional spherical lapping process to quick remove the sub-surface damage (SSD) layer and to get the accurate radius of best fit sphere of aspheric surface with fine surface texture simultaneously. The polishing and metrology processes were performed by using Zeeko IRP1000 polisher and QED ASI stitching interferometer. A ?150 mm mirror with freeform surface was completed.

8841-38, Session PMon

Using the toroidal and cylindrical lenses to project the RGB LEDs sources on the lens array with elliptic solid angle calculation for the DLP projector

Wen-Shing Sun, National Central Univ. (Taiwan)

We present an illuminated projection system design to improve the efficiency and uniformity. First, the light sources of RGB LEDs pass through the toroidal and cylindrical lenses to image on the lens array. For the image, the vertical and horizontal magnifications are different. The magnifications can match the rectangular size of lens array. We use the elliptical solid angle calculation and enhance the efficiency of the light source. Second, we use lens array to split the light shape and to form many light sources, and design an uniform illumination system for projector. Third, the light sources pass through the projector lens to the screen. We analysis the image quality for the projector lens, and compute the efficiency, uniformity, and CIE chromaticity coordinate on the screen.

8841-39, Session PMon

Three dimensional point spread function of a high aperture optical system

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The paper presents the mathematical technique for precise calculation of the three dimensional point spread function (3D PSF) of a high aperture optical system. The comparison analysis shows that many known techniques for calculation of the point spread functions are generally based on Fresnel or Fraunhofer approximations. It causes the sufficient inaccuracy when high aperture optical systems are investigated. The proposed technique is based on Huygens-Fresnel principle: spherical wave at an exit pupil is considered as a numerous set of elementary secondary light sources. These sources emit spherical coherent electro-magnetic waves. All these waves form a definite distribution of summarized complex amplitudes in three dimensional space near the focal point. This distribution of the complex amplitudes is used for calculation of the distribution of effective intensities which take into account the influence of inclined elementary wave fronts. The limitations of possible approximations of the 3D PSF are analyzed. The algorithms for fast calculations of 3D PSF are described and illustrated by the calculated cross-sections of 3D PSF of typical microscope objectives. The links 3D PSF with a three dimensional line spread function and a three dimensional edge response functions are studied. The techniques for comparison of the calculated and measured data about 3D PSF are discussed.

8841-40, Session PMon

Enhancement effect of terahertz wave in split ring resonators

Qinglong Meng, Bing Zeng, Wenyi Shao, Bin Zhang, Sichuan Univ. (China)

Based on the theory of split ring resonators (SRRs) and the rigorous

theory of electromagnetic field, the spatial distributions of the electric field and electric energy density in split ring resonators with different structures such as square, circle and triangle have been analyzed. The variation of electric energy density with different terahertz (THz) frequencies has also been investigated. It can be shown from our numerical simulation results that the electric field enhancement effect occurs in the split ring resonators with square, circle and triangle structures and the electric field near the opening is obviously stronger than that in other regions, especially in the gap of the split ring resonators. The maximum of the electric energy density appears in the opening of the SRRs and the electric field is obviously stronger near the resonance frequency of the SRRs. The results obtained in this paper have important significance on the design of the split ring resonators and the function of resonant magnetic response of left hand materials (LHMs).

8841-41, Session PMon

Multi-agent system in automatic light power balance in optical networks

Martin Slapak, CESNET z.s.p.o. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Miloslav Hula, CESNET z.s.p.o. (Czech Republic)

An automated power balancing was performed on testbed with two amplifiers, two 75 km long fibre spans and one attenuation element. The parameters of link are measured by modular remotely controlled device FTB500 with Pocket Blazed FTB8510G module which puts 10Gbit traffic through link.

Balancing software was designed as multi-agent system with three types of agents. The first type is amplifier controller, which comunicates with assigned amplifier. The core type of an agent is „balancer“ which performs actions according to proposed balancing algorithm. The last one handles GUI which allows human operator to control the whole balancing process.

The proposed balancing algorithm is robust and is capable to bring the link from unknown (eg. some amplifiers could be switched off at beginning) to functional state with bit error rate about 1.0E-12. The balancing takes approximately 3-5 minutes because we measure BER only for several seconds after an each change. It is extremely fast with regard to the time needed to measure the BER with predetermined confidence interval width.

The driving current in the amplifiers was decreased approximately by 23 % from the initial state. We cannot exactly say how much it changed the real lifetime of each pump diode. It depends exponentially on the tempeture. But a possitive impact of a lower driving current to lifetime is evident.

8841-42, Session PMon

The multichannel spectral device with transmitting analyzed optical signals by the optical fiber for the liquid propellant rocket engine diagnostics

Mikhail A. Vaganov, Oleg D. Moskaletz, St. Petersburg State Univ. of Aerospace Instrumentation (Russian Federation)

Recently spectroscopic methods of diagnostics of the liquid propellant rocket engines for prevention of emergencies become topical. These methods allow to receive information about engine’s condition by carrying out spectral measurement of rocket blast radiation. Such diagnostics is based on tracking appearance of spectral lines of engine’s constructional materials in spectrum of rocket blast radiation.

The multichannel optical spectral device considered in this paper makes the contactless spectrum analysis of optical radiations that allows to use this spectral device for diagnostics of the liquid propellant rocket engines. The novelty of this spectral device lies in application of the fiber-optical bundle and N parallel channels of the spectrum analysis. Each channel contains the narrow-band optical filtration which has been set on the certain wave length. The fiber-optical bundle is used for transmitting analyzed optical radiation on a safe distance for device.

This method of the contactless rocket engine diagnostics allows to except a direct contact of the spectral device with the field of rocket blast radiation and to eliminate negative influence of the engine on the spectral device, for example the acoustic impact.

Such diagnostics is very important for providing flight safety both of civil and military aircrafts.

The results of experimental research are given. These results prove functionality of the multichannel optical spectral device.

The multichannel optical spectral device realizes ideas of patent ? 86734 of the Russian Federation.

8841-43, Session PMon

Fabrication of subcutaneous veins phantom for vessel visualisation system

Kai Cheng, Doshisha Univ. (Japan); Kazuyuki Narita, Doshisha Univ (Japan); Eiji Nakamachi, Yusuke Morita, Doshisha Univ. (Japan); Norihiro Honda, Kunio Awazu, Osaka Univ. (Japan)

The technique of subcutaneous veins imaging by using NIR (Near Infrared Radiation) is widely used in medical applications, such as the intravenous injection and the blood sampling. In the previous study, an automatic 3D blood vessel search and automatic blood sampling system was newly developed. In order to validate this NIR imaging system, we adopted the subcutaneous veins in the human arm and its artificial phantom, which imitate the human fat and blood vessel. The human skin and subcutaneous vein is characterized as the uncertainty object, which has the individual specificity, non-accurate depth information, non-steady state and hardly to be fixed in the examination apparatus. On the other hand, the conventional phantom was quite distinct from the human’s characteristics, such as the non-multilayer structure, disagreement of optical property. In this study, we develop a multilayer phantom, which is quite similar with human skin, for improvement of NIR detection system evaluation. The phantom consists of three layers, such as the epidermis layer, the dermis layer and the subcutaneous fat layer. We embedded a blood vessel inside the subcutaneous fat layer. We use the intralipid to imitate the optical scattering characteristics of human skin, and the hemoglobin and melanin for the optical absorption characteristics. In this study, we did two subjects. First, we decide the fabrication process of the phantom and confirmed the process was stable. Second, we compared newly developed phantoms with human skin by using our NIR detecting system, and confirm the availability of these phantoms.

8841-44, Session PMon

Thermal shock and stress with infrared optical domes and materials

Youtang Gao, Nanyang Institute of Technology (China)

The development of infrared optical materials is always closely related to the research and exploration of material science. The infrared optical domes bears shock and produces stress when the infrared optical domes mounted on the missile moving at a high speed is shocked by high temperature. According to aerodynamics theory and thermo shock theory, the surge current will be transferred to optical parts through holding up layer and warms the surface of optical parts when infrared optical parts are shocked by high temperature. A compress stress is formed on the hot external surface of optical parts forms and a tension stress is formed on the internal surface or optical parts under the circumstance of the edge of optical parts being fixed. The windows of optical parts become curvature radius of lens with the function of pressure difference which can cause aberration change. The brittle fracture of material will be caused if peak stress is beyond the strength which is permitted for infrared materials. Therefore, limits to design of windows thickness is proposed in this paper.

8841-45, Session PMon

Near-infrared imaging system for detecting small organic foreign substances in foods

Hiroto Tashima, Tsuneaki Genta, Yuya Ishii, Takeshi Ishiyama, Shinichi Arai, Mitsuo Fukuda, Toyohashi Univ. of Technology (Japan)

Contamination of foods with foreign substances is a serious problem because it often has negative effects on health. However, detecting small organic substances in foods is quite difficult because they are undetectable with traditional inspection apparatus. In this work, we developed new equipment that detects small organic substances at high speed, applying a near-infrared (NIR) imaging technique. The absorption spectra of various foods were measured, and the spectra showed low absorbance at wavelengths from 600 nm to 1150 nm. Considering the observable wavelength of a CMOS camera, which enables high-speed imaging (~30 cm/sec) and has high dynamic range (90 dB), superluminescent diodes (SLD) with a wavelength of 830 nm were selected as a light source. We arranged 40 of the SLDs on a flat panel and placed a diffusion panel over them. As a result, uniformly distributed light with an intensity of 0.26 mW/cm2 was supplied to an area of 6.0 cm x 6.0 cm. Insects (3 mm width) and hairs (0.11 mm diameter) were embedded in stacked sliced ham with a total thickness of 5 mm, and the transmission images were observed. The insects and hairs were clearly observed as dark shadows with high contrast. Furthermore, we compensated the images, using a software developed in this study for eliminating low spatial frequency components in images and improving sharpness and contrast. As a result, the foreign substances were more clearly distinguished in the 5-mm-thick ham. In conclusion, we developed equipment that detects small organic substances in foods, using an improved NIR imaging technique.

8841-46, Session PMon

Application of the light field for a simulation to evaluate the MTF of optical lens systems using rendering

Shuma Horiuchi, Manabu Yamamoto, Tokyo Univ. of Science (Japan)

Simulation using rendering can evaluate the modulation transfer function (MTF) of optical lens systems and advantages to design a optical lens systems. Rendering is typically used in three-dimensional computer graphics (3D CG) with the ray tracing method. This simulation method corresponds to an experimental measurement of the MTF using bar-target test charts, and therefore allows an analysis of the resolving power of shift-variant optical systems that are difficult to evaluate with conventional methods based on the point spread function (PSF). However many sampling number of rays are necessary to obtain the radiance distribution which is reduced the variance. Therefore the computational time increases in proportion of the analyzed spatial frequency. Then in this paper, we proposed the technique to apply the light field in the method. The technique records the light field which is a function that describes position and direction of rays on the entrance pupil plane of the lens system. The image formation is constructed from the light field with test charts of every spatial frequencies. The computational time that the image formation is constructed is very short as compared to ray tracing in the lens system. Therefore the MTF for each spatial frequency can be obtained very fast. This paper outlines the recording method and the format of the light field.

8841-47, Session PMon

Holographic recording method using shift multiplexing system with spherical reference beam

Yuta Nagao, Kaito Okubo, Hiroyuki Kurata, Takaaki Matsubara, Manabu Yamamoto, Tokyo Univ. of Science (Japan)

Recently, along with the wider use of high-speed information networks and multimedia, it is increasingly necessary to have higher-density and higher-transfer-rate storage devices. Therefore, research and development into holographic memories with three-dimensional storage areas is being carried out to realize next-generation large-capacity memories. The mainstream of the multiplexing system in the world is the angle multiplexing method however it has some problems for example it costs too much and its control is quite severe. Therefore we studied about shift multiplexing method using spherical reference beam to store data more than angle multiplexing. Generally, there is only one direction to allow multiplexing in shift multiplexing?method, however in this paper we examined about shift selectivity of track direction (x-axis), radial direction (y-axis) and vertical direction (z-axis) of the disk medium. Combining these three different kinds of directions, we found a possible multiplexing way to achieve several tera bits per inch square density recording. In this experiment, we recorded data in the medium which material is photopolymer and 1.5mm thick. In addition, using a high NA objective lens for the reference beam, we experimentally succeed to make data density higher.

8841-48, Session PMon

A framework of cloud supported collaborative design in optical glass moulds based on aspheric measurement

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At present, lens molding (hot pressing) technology has become a popular method to manufacture a lot of small aspheric glass lenses in order to reduce the cost and improve the efficiency. In glass lens molding, the key factor lies in the accurate design of precision optical aspheric moulds. Aspheric mould design includes the top-down design and reversal design. In this paper, a new framework of reversal design is proposed combining with cloud supported collaborative design (CSCD) based on aspheric measurement. The framework is a kind of collaborative platform, which is composed of eight modules, including the computerized aspheric precision measurement module (CAPM), computer-aided optical design of aspheric lens system (CAOD), computer-aided design of lens mould (CAD), computer simulation of lens molding module (CSLM), computer-aided experiments of lens & moulds (CAELM), data analysis module (DAM), optical product lifecycle management module (OPLM) and cloud computing network module (CCNM). In this framework, the remote clients send an improved requirement or fabrication demand about optical lens system through CCNM, which transfers this signal to OPLM. In OPLM, one main server is in charge of the task distribution and collaborative work of other six modules. The first measurement data of aspheric lens are produced by clients or our proposed platform CAPM (laser interferometer or profilometer), then are sent to CAOD for optimization and the electronic drawings of lens moulds are generated in CAD module. According the design drawings, the CSLM could give the lens-molding simulation parameters through FEM software such as MSC. Marc or Deform. The simulation data are used for the second design of moulds in CAD module. In this case, the moulds could be fabricated by diamond turning or grinding in CAELM by ultra-precision machine, and the aspheric lens could be also produced by lens-molding machine in CAELM. At last, the final shape of aspheric lens could be measured

in CAPM and the data analysis could be conducted in DAM module. Through the proposed framework, all the work described above could be performed coordinately. And the optimum design data of lens mould could be realized and saved, then shared by all the work team.

8841-49, Session PMon

Design for adjustable optical system of liquid filled lens

Dein Shaw, Hui-An Hsieh, National Tsing Hua Univ. (Taiwan)

Most of the image capture modules use flat and rigid sensors, but the flat sensor surface can't match the curvy focal surface of a single lens system perfectly. The error between the off-axial image of flat sensor and the focal surface, call aberration, limits the image quality when the image comes from a lens. One solution is using multiple individual lenses to force the image flat and match the focal surface, but it also causes the whole module hard to be compact. The requirement for higher image quality and less volume of module motives the study of liquid lens and flexible sensor system. In this research, we design a optical integrated module including a liquid-filled lens, a flexible sensor membrane and a self-adjusted optical compensation device. We focus on the optical relationship between the liquid-filled lens and the sensor membrane to make the system has good optical characters. According to compensation function, this module compensates the optical character between lens and sensor membrane to obtain a clear image by adjusting the internal pressure and volume of the liquid in the liquid filled optical system. The curvy sensor membrane has better performance than flat type sensor in both the image quality of MTF, aberration and angle of view for a single lens optical system. The research can be applied in the fields of the adapter lens system of digital camera, self-compensation optical system and security optical devices, etc.

8841-50, Session PMon

Optical-digital system for spectra analysis from aqueous solutions of textile dyes

Alfonso Padilla-Vivanco, David Villegas-Hernandez, Valente Licona-Carrasco, Univ. Politécnica de Tulancingo (Mexico)

Textile wastewater treatment is still a great environmental problem today. Azo dyes represent the largest class of textile dyes. Due to the large number of aromatic groups present in these molecules and their stabilities, most azo dyes are nonbiodegradable. Many conventional treatment methods have been found to be ineffective for the decolorization and degradation processes. Chemical processes such as chlorination and ozonation are the most frequently used methods for removal of the textile dyes from wastewater. Others process such as flocculation, reverse osmosis, and adsorption onto activated carbon had been examined. However, these processes only transfer the contaminants from one phase to another, and further treatments are required. Namely, the advanced oxidation processes have been extensively investigated. Among these processes, heterogeneous photocatalysis is an emerging destructive technology leading to total destruction of most of organic pollutants. In some cases, the degradation is conducted for dissolved compounds in water with ultraviolet-illuminated TiO_2. Here, the main idea is to implement a spectroscopic system to measure the concentration of textile dyes which are dissolved in aqueous solutions.

8841-51, Session PMon

Analysis and implementation of a digital holographic imaging system for extended objects

Martin Hernández-Romo, Alfonso Padilla-Vivanco, Carina Toxqui-Quitl, Univ. Politécnica de Tulancingo (Mexico)

Holography is the method of capture and reconstruction of 3-D objects, which has numerous applications in optical metrology. Specifically digital holography offers several advantages over classical holography as it is to avoid chemical treatments, object reuse numeric access to the phase and amplitude of the objects. In particular we use an optical system based on off-axis holography interferometer which serves to make the recording of holographic filters from optical images of extended objects and reference beams. Some designs avoids the presence of shadows in the hologram after that the hologram recovery can be calculated from the wavelet filter coefficients and the peak 2D wavelet transform. The object reconstruction can be improved in the ideal case by an coherent imaging system which is difraction limited. Experimentally has been found that a combination of negative and positive lenses can formed images with a acceptable resolution. In this work, the interest is determine the imaging system by means a combination of commercial lenses.

8841-52, Session PMon

Design of highly-efficient vertical p-n junction type Si optical modulator with low driving voltage

Chan-Min Kang, Jungho Park, Seulki Kim, Jinsik Kim, Korea Univ. (Korea, Republic of)

Vertical p-n junction carrier-depletion type silicon phase modulator with low driving voltage was designed and implemented using Mach-Zehnder interferometer. The free-carrier plasma dispersion effect was considered to increase the electro-optic effect of silicon based modulator. The modulation mechanism is mainly based on the free-carrier plasma dispersion effect in vertical p-n junction. Silicon-on-insulator wafer was used to fabricate the modulator and coplanar strip electrodes were designed to transmit the RF signal with 50 Ω matching. COMSOL Multiphysics and High Frequency Structure Simulator(HFSS) were used to find optimum dimensions of modulator and to simulate RF characteristics of modulator's electrode, respectively. Waveguide in Mach-Zehnder interferometer was designed for single mode operation. The device could be operated with very low π-phase-shift voltage-length ($V\pi L$) of 0.57 V•cm. Driving voltage of a 2 mm long modulator is 2 V and cut-off frequency is up to 25 GHz. Such a highly efficient modulating capability with low power consumption makes the integrated silicon photonic chips for next generation communication networks possible.

8841-53, Session PMon

Theoretical considerations in radiometer design

José G. Suárez-Romero, Instituto Tecnológico de Querétaro (Mexico)

This work considers typical radiometers that measure the radiance of sources or of some surface (due to reflection). The most important thin in a radiometer is its optical cavity, which defines the solid angle of measurement. In case of instruments that use lenses, lens diameter and focal length define the solid angle. Radiometer design takes care that the solid angle subtended by the optical cavity be minor that the solid angle subtended by the source to be measured, however no considerations are taken on the length of the cavity. In this work it is discussed theoretical limitation in the design of radiometers, particularly the influence of radiometer length (the cavity length). Theory of partial coherence is used to obtain the instrument function and to show how the length of the instrument affects measurements.

8841-54, Session PMon

Design, fabrication, and metrology of polymer gradient-index lenses for high-performance eyepieces

James A. Corsetti, Anthony Visconti, Kejia Fang, Peter McCarthy, Greg R. Schmidt, Duncan T. Moore, Univ. of Rochester (United States)

High-performance eyepiece designs have been carried out using both spherical and radial gradient-index (GRIN) elements. Eyepiece designs of both geometries are shown to offer superior imaging performance with fewer elements when compared to purely homogeneous systems. These GRIN lenses are formed from monomer diffusion between polymethyl methacrylate (PMMA) and polystyrene (PSTY) during the polymerization process, resulting in a copolymer of the two homogeneous materials.

A process for fabricating spherical GRIN elements is discussed where copolymer axial GRIN blanks are thermally compressed using spherical surface molds. This process curves the nominally-straight isoindicial surfaces of the axial GRIN rod to be consistent with the shape found during optimization of the design. Once compressed, the spherical blanks are diamond-turned for final surface figure and finish. Measurement of the GRIN profile is carried out using the Schmidt immersion technique in a Mach-Zehnder interferometer. Tolerances specific to GRIN elements are identified and determined to be readily achievable using the aforementioned manufacturing process.

The methodology of generating GRIN elements of the radial geometry is also discussed. By pumping the two monomers into a rotating cylindrical chamber (for this purpose, mounted to a lathe) a rotationally-symmetric GRIN profile is formed as a result of the diffusion process. The centrifugal force of the lathe causes the heavier material (PMMA) to settle at the outside of the chamber and the lighter material (PSTY) at the center. Preliminary results for GRIN elements fabricated in this way have been successful and are shown.

8841-28, Session 7

Fabrication of gapless microlenses on spherical surface by multi-replication process

Yi-shiuan Cherng, National Taiwan Univ. (Taiwan)

Artificial compound-eye structure has been studied recently due to its great applications of wide field-of-view imaging and backlight modules. However, fabrication process for microstructures on curvilinear surface has a lot of difficulties since traditional fabrication techniques are planar. In this paper, a simple and low-cost method to fabricate microlenses on spherical surface was demonstrated. Microlenses with high fill factor were formed by thermal reflow technique, followed by multiple replication processes to transfer the microlenses from planar substrate onto spherical surface. During the process, we made a curved mold with concave microlenses, which allowed this method to be duplicable easily. Polydimethylsiloxane (PDMS) elastomer was employed as the material of both microlenses and mold due to its flexibility and transparency for visible light. To prevent microlenses from being damaged during the release procedure, surface treatment using Trichloro (1H,1H,2H,2H-perfluorooctyl) silane was applied before every replication process. Several PDMS domes covered with hexagonal or square microlenses on the surface were fabricated successfully. The diameter of each microlens was about 200 μm and the pitch of array was 220 μm. The radius of curvature of the spherical surface was about 6.2 mm. The uniformity of microlenses was analyzed through the intensity distribution of focused spots. Imaging performance of microlenses was shown, presenting a wider view-angle focusing property. The curved microlens arrays were combined with image sensor, and clear images of objects at different distance are shown. The experimental results showed a high potential for curved microlens arrays being applied to compact mobile camera lens.

8841-30, Session 7

SNR parameter test system of MCP In vacuum system

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The core component of night vision system is Image intensifier. Research and production for the third generation of low light level image intensifier device are in progress in China. Fourth-generation image intensifier imaging mechanism is under Pre-Research. Screen, microchannel plate and the cathode are the main parts of an image intensifier. The important performance parameters such as resolution and signal-to-noise-ratio(SNR) of image intensifier depend on the Comprehensive performances of screen, the microchannel plate and cathode. Noise characteristic of the microchannel plate (MCP) is an important indicator of the evaluation of image intensifiers, while the present theory suggests that MCP is a major noise source of the image intensifier. In order to detect the MCP-generated noise, a vacuum system and designed the test method of the noise factor of MCP have been established. The noise factor of the MCP is measured using the test set-up with microchannel plate MCP signal to noise ratio parameter detection device in the vacuum system. It is can be used to judge the quality of the MCP scientifically .The experiments verify this test system is advanced, and the test results are reliable. This test system Provide a technical to promote the image intensifier research, and experience to testing other parameters or in other areas of research.

8841-31, Session 7

Er3+-doped fiber-based Mach- Zehnder interferometer with mechanically-induced long-period fiber gratings

Grethell G. Perez-Sanchez, José Alfredo Alvarez-Chavez, Ctr. de Investigación e Innovación Tecnológica (Mexico)

There are a few semi-conductor, multiple-wavelength, high-performance sources already available for ITU-T channel generation in DWDM systems. The 200 Ghz barrier has imposed a limitation to such sources. An option for overcoming such a limitation is a super-continuum, all-fibre source working in the amplified spontaneous emission regime. Amplified spontaneous emission from an Er-doped fiber spectrum is well-suited for broadband applications as its optical nature permits emission, amplification and detection within at least 100nm bands, via channel selection through either mode-locking or saturable absorber methods. Consequently, in this work we propose a preliminary Er-doped fiber based Mach-Zehnder interferometer, made with mechanically-induced, long-period, fiber gratings, which generates a fringe pattern ranging from 1450 to 1650 nm, which could be employed in modern DWDM systems. The aforementioned MZI characteristics are of great interest for the development of all-fiber devices that could produce and even select a few channels in the 1550nm region, the transmission window of interest for ultra-long haul optical communication systems. A full set of optical characterization and results will be included in the presentation.

8841-32, Session 7

Further results in measuring water ice buildup on optical components in cryogenic vacuum chambers

Trevor M. Moeller, L. M. Smith, Frank G. Collins, James P. Rogers, The Univ. of Tennessee Space Institute (United States); Jesse M. Labello, Heard S. Lowry, Dustin H. Crider, Arnold Engineering Development Ctr. (United States)

Experiments presented in a previous paper [1] established proof-of-principle that water, the most prevalent contaminant in high-vacuum cryogenic systems, initially collects on the surfaces of optical components as a thin film of ice, and thus can be detected and its thickness measured via multiple-beam thin-film interference phenomena. In those earlier experiments, a molecular sieve zeolite in a canister external to a vacuum chamber served as a water source, while the buildup of ice was measured using a HeNe laser beam reflected off the surface of a mirror with a quartz crystal microbalance (QCM) used for verification of the mass accumulation. Additional experiments have improved upon the techniques used earlier and provided further insight into the ice accumulation process. Use of a shorter wavelength (450 nm) laser in conjunction with a first-surface gold mirror produced greater depth of modulation and thus increased signal-to-noise ratio in the light interference. Data reduction using cross-correlation analysis over single-period interference records provided more accuracy and precision in the ice thickness measurements. Ice buildup under varying pressure and temperature ranges established baseline conditions for transparent thin-film deposition, and the transition to ice fracture and specular reflection. These recent experiments have demonstrated that the optical monitoring of ice accumulation via multiple-beam interference is applicable over a wider range of mass and thicknesses than the conventionally-used QCM method.

[1] T. M. Moeller, L. M. Smith, F. G. Collins, J. M. Labello, J. P. Rogers, H. S. Lowry, D. H. Crider, “Measurement of the accumulation of water ice on optical components in cryogenic vacuum environments,” Optical Engineering, Vol. 51, No. 11, November 2012, pp. 115601-1 to 115601-8.

8841-33, Session 7

Ionic polymer metal composite to achieve optical zoom function in a compact camera

Wei-Shiang Chen, National Taiwan Univ. (Taiwan)

Nowadays, there are many popular electronic devices consist of optical focus zooming systems. It is the trend to minimize optical systems in the portable devices. For this purpose, we used deformable mirrors in optical systems that can make them thinner and slighter. The Ionic-Polymer Metal Composite (IPMC) is the critical component in our design of the deformable mirror. It has good bending feature and can be driven at low voltage (less than 5 volts). The IPMC fabrication processes contain three steps: acid clean, initial compositing process and surface electrode plating process. We use Nafion in the IPMC fabrication. In order to create the desirable electrode shape, we make the Nafion covered by a shadow mask to make the elliptic pattern electrode. After the IPMC is completed, we deposit aluminum on one side as a reflective surface to finish our deformable mirror. In our experiment, we put the two deformable mirrors in the optical zoom module. This module consists of three biconic mirrors and the two deformable mirrors. When we applied voltages on deformable mirrors, the reflective light is successfully focused after the deformation of elliptic IPMC. At the tele-end, the curvatures of two deformable mirrors are all zero. While at wide-end, the first deformable mirror is actuated to convex in 25 diopter (m-1) and the second deformable mirror is actuated to concave in 65 diopter (m-1). The zoom ratio of this module can achieve to 1.7 times. The deformable mirror can be changed from flat to 65 diopter (m-1) by about 3 volts.

8842-29, Session PMon

Utilizing perkinelmer infrared spectroscopy to achieve a full spectrum at ppm level

Chunhong Xiao, PerkinElmer, Inc. (United States)

Infrared spectroscopy has been widely used for qualitative and quantitative analysis, including incoming raw material quality control and impurity&contamination identification, however, it has always been a challenge to get a full spectrum at ppm level. Some ppm quantitative analysis was done based on limited spectral information within the high wavenumber region or a particular small region. With limited spectral range, it is not feasible to do qualitative analysis. In this presentation, we explored the IR application on material detection and identification at ppm level with a high sensitivity MCT detector system.

One of the materials studied here is caffeine. Caffeine is widely used in food and drug, including all kinds of drinks, tea, soda and coffee. Depending on the category, it is regulated differently by FDA. The safe level defined by FDA is 0.02% or less, which is 200ppm or less.

Spectra were taken at 4cm-1/4co-adds with PerkinElmer MCT IR spectrometer. 300 ppm caffeine solution was made by adding 300 microgram caffeine into 10 milliliter dichromethane (DM). 30 ppm caffeine was diluted from the 300 ppm solution. Caffeine spectra at ppm level were retrieved by subtracting the spectrum of 300 ppm caffeine in DM from DM spectrum (Figure 1).

Some other materials were also studied at ppm level in different solvents. With a full spectrum of the ppm level solutions, now IR can be used for not only quantitative but also qualitative analysis for low level detections.

8842-30, Session PMon

White light holograms: made from scratch

Dennis Tierney, Xavier Univ. (United States); Erna Frins, Univ. de la República (Uruguay); B. Hils, Wolfgang Dultz, Johann Wolfgang Goethe-Univ. Frankfurt am Main (Germany); Heidrun Schmitzer, Xavier Univ. (United States)

Scratch holograms are produced by engraving circular patterns with dividers on a polished surface. When illuminated with a more or less point like light source, each circular groove reconstructs one image point. The light source does not need to be coherent and can be very broadband. Wheatstone described this effect already in the 19th century and it was rediscovered in the 1990's; particularly William Beaty developed this effect further to display three dimensional images. Scratch holograms are not based on the interference of light, but rather on the conservation of the light's momentum during scattering from a groove. This scattering is similar to diffraction, but without the secondary effect of interference. Scratch holograms are independent of the wavelength and can therefore be considered real white light holograms. A theoretical modelling using Born's approximation supports this interpretation. To demonstrate this experimentally we use the fact that the path of light is reversible and show that circular patterns can be fabricated with a stream of small particles coming from the nozzle of a sand blast unit exiting a tilted slit.

8842-32, Session PMon

System of polarization correlometry of biological liquids layers polycrystalline structure

Taras Boychuk, Bukovinian State Medical Univ. (Ukraine); Alexander Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Ozar Mincer, Bukovinian State Medical Univ. (Ukraine); Pavlo O. Angelsky, Natalia Bodnar, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Liliya Bizer, Bukovinian State Medical Univ. (Ukraine); Boris Oleinichenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

As a base for modeling the optical properties of blood plasma we use the conception of anisotropy

- blood plasma can be considered as a two-component amorphous-crystalline structure;
- optically anisotropic – luquid-crystalline phase consisting of a set of optically uniaxial birefringent liquid crystals of various types: spherulitic globulins and scicular albumins with circular and linear birefringence.

It is shown that statistic approach to the analysis of complex degree of mutual coherence distributions of blood plasma are effective for differentiation of acute and gangrenous conditions have been analytically substantiated.

From the obtained data about the coordinate distributions of CDMC of blood plasma layers both groups can see that:

- The average and dispersion of CDMC distributions differ insufficiently within 1.75 – 2.5 times.
- The asymmetry values of CDMC distributions of the investigated samples differ by 2.5 - 4 times; the excess values – by 1.5 – 3.5 times.

A model of the effusion polycrystalline networks optical anisotropy of appendicitis has been suggested and the method of CDMC diffentation of linear (a phase shift between the orthogonal components of the laser wave amplitude) and circular (the angle of rotation of the polarization plane) birefringence is developed.

8842-33, Session PMon

The system spatial-frequency filtering of birefringence images of human blood layers

Taras Boychuk, Bukovinian State Medical Univ. (Ukraine); Alexander Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Ozar Mincer, Bukovinian State Medical Univ. (Ukraine); Pavlo O. Angelsky, Boris Oleinichenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Natalia Bodnar, Liliya Bizer, Bukovinian State Medical Univ. (Ukraine)

As a base for analyses of processes providing formation of polarization-inhomogeneous images of human blood, we use the next optical model:

- optical properties of human blood are determined as those of a two-component structure – формені епементи - пπазма;
- crystalline component of forming elementa are optically;
- blood plasma crystalline component is an architectonic net consisting of amino-acid liquid crystals with linear birefringence.

Our analysis of the parameters determined experimentally has shown that the following parameters are diagnostically sensitive in observation of inflammatory processes:

- statistical moments of the third and the fourth orders in distributions for the amount of extreme values of phase shifts delta=0.5? in laser images for human blood health's and sick patients – differences between them reach 1.7 - 2.4 and 2.4 - 4.1 times;
- distributions of extreme values of phase shifts for the phase maps describing human blood for healthy and sick patients are, respectively, statistical and fractal;

Thus, one can conclude:

1. Human blood, independently of their physiological state, contains phase-modulating optically anisotropic network of biological crystals.
2. Ascertained and grounded is a set of criteria for phase diagnostics

of pathological and cancer processes as being based on statistical (statistical moments of the first to the fourth orders) and fractal (fractal dimensionality) analyses of phase distributions in laser images of human blood.

8842-34, Session PMon

Fabrication of universal all-optical gates and switches by implementation of optical cavity based on Brewster-angle phenomenon

Akbar Rahmani-Nejad, Maharan Engineering Corp. (Iran, Islamic Republic of)

We used Brewster's angle phenomenon and an optical cavity as a decisive method to implement all-optical logical gates and switches. A microcavity is attached by a micro-fiber coupler to two optical signal. The first signal that is called control signal is coupled such that the optical signal travel es inside the cavity parallel to the main axis and to be confined. The second optical- that is parallel polarized- signal is coupled slightly upper than Brewster's angle. This is called the data-signal. An optical crystal having refraction index "n" is inserted in the optical cavity. When there is no control optical signal, a portion of data-signal is reflected back. by inducing control signal refractive index of the crystal inside the cavity increases to about "0.2-0.3n" more than previous value this is enough to increase Brewster's angle about several degrees that results to complete deletion of reflected parallel-polarized beam of data-signal. Due to enhancing specification of microcavity the threshold intensity is completely feasible and economical. On the other hand due to crucial asymptotic characteristics of Brewster's angle phenomenon, there is no reflected data-signal that can be considered as commercial optical switch or optical NOT gate. By inducing of two control signal and fixing the level of required change of refractive index corresponding to sum of the intensity of two control signals a NAND all optical gated is fabricated. There is a SOA to amplify reflected control to non-reflected incident beam and a polarizer when there is no control signal.

8842-35, Session PMon

Singular microscopy of biological layers for diagnostics and classification of their optical properties

Taras Boychuk, Ozar Mintser, Bukovinian State Medical Univ. (Ukraine); Alexander Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

This work is aimed at ascertaining the possibilities to diagnose and classify phase-inhomogeneous layers (PhIL) of various types (surface-scattering, subsurface-scattering and bulk-scattering ones) by determination values and ranges for changing the statistical (moments of the 1-st to 4-th orders), correlation (autocorrelation functions) and fractal (logarithmic dependences for power spectra) parameters that characterize coordinate distributions for polarization-singular states in PhIL laser images.

8842-36, Session PMon

Multiparameter correlation microscopy of blood plasma polycrystalline networks in the diagnosis of cancer tissues of female reproductive system

Vitaliy N. Balazyuk, Galina Koval, Volodimir G. Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

To characterize the degree of consistency of parameters of the optically uniaxial birefringent protein nets of blood plasma a new parameter – complex degree of mutual anisotropy (CDMA) is suggested. The technique of polarization measuring the coordinate distributions of the complex degree of mutual anisotropy of blood plasma is developed.

A model of the effusion polycrystal networks optical anisotropy of appendicitis has been suggested and the method of CDMA diffentation of linear parameters (a phase shift between the orthogonal components of the laser wave amplitude) and circular (the angle of rotation of the polarization plane) birefringence.

8842-37, Session PMon

System of space: Frequency filtering of linear and circular birefringence in cancer diagnosis

Mykola Raranskiy, Galina Koval, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

Our research is aimed at designing an experimental method of Fourier's laser polarization phasometry of the layers of human effusion for an express determining the potentialities of diagnostics of pathological changes in the endometrial tissue of female reproductive system.

The main idea of such an approach lies in the fact that spatial-frequency structure of the Fourier form of the laser image of the polycrystalline network of human effusion is different for its large scale albumin and small scale protein structures. Therefore, through space-frequency filtering one can mainly select either low-frequency (with linear birefringence) or high-frequency (with circular birefringence) components which by means of reverse Fourier transformation can be converted into corresponding "separated" laser images.

8842-38, Session PMon

Polarization-phase imaging of biological fluids polycrystalline structure

Mikhailo Sakhnovskiy, Vitaliy N. Balazyuk, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

Our research is aimed at designing an experimental method of Fourier's laser polarization phasometry of the layers of human effusion for an express diagnostics during surgery and a differentiation of the degree of severity (acute - gangrenous) appendectomy by means of statistical, correlation and fractal analysis of the coherent scattered field.

A model of generalized optical anisotropy of polycrystal networks of albumin and globulin of the effusion of appendicitis has been suggested and the method of Fourier's phasometry of linear (a phase shift between the orthogonal components of the laser wave amplitude) and circular (the angle of rotation of the polarization plane) birefringence with a spatial-frequency selection of the coordinate distributions for the differentiation of acute and gangrenous conditions have been analytically substantiated.

8842-39, Session PMon

Multidimensional Mueller-matrixes microscopy of biological phase-inhomogeneous layers

Alexander V. Dubolazov, Artem O. Karachevtsev, Maxim V. Sidor, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

Specific features of the formation of local and statistical polarization structures of laser radiation scattered in phase-inhomogeneous layers (PIL) of biological tissue (BT) were studied. The distribution of azimuth and eccentricity of boundary field polarization was found to correlate with the orientation-phase structure of multifractal PIL. A method of polarization phase reconstruction of BT architectonics was suggested.

Polarization fractallometry of 2DSi parameters of Mueller matrixes of BT images is effective in diagnostics of changes of coordinate distributions of orientations and optical anisotropy of their architectonic nets, formed by the collagen bundles.

8842-40, Session PMon

A novel and compact spectral imaging system based on two curved prisms

Yunfeng Nie, Xiangli Bin, Jinsong Zhou, Yang Li, Academy of Opto-Electronics (China)

As a novel detection approach which simultaneously acquires two-dimensional visual picture and one-dimensional spectral information, spectral imaging offers promising applications on biomedical imaging, conservation and identification of artworks, surveillance of food safety, and so forth. A novel moderate-resolution spectral imaging system consisting of merely two optical elements is illustrated in this paper. It can realize the function of a relay imaging system as well as a 10nm spectral resolution spectroscopy. Compared to conventional prismatic imaging spectrometers, this design is compact and concise with only two special curved prisms by utilizing two reflective surfaces. In contrast to spectral imagers based on diffractive grating, the usage of compound-prism possesses characteristics of higher energy utilization and wider free spectral range. The seidel aberration theory and dispersive principle of this special prism are analyzed at first. According to the results, the optical system of this design is simulated, and the performance evaluation including spot diagram, MTF and distortion, is presented. In the end, considering the difficulty and particularity of manufacture and alignment, an available method for fabrication and measurement is proposed.

8842-1, Session 1

Cluster eye camera using microlenses on parabolic surface

Hui-Kai Shen, Guo-Dung John Su, National Taiwan Univ. (Taiwan)

There are two main types of imaging systems that exist in nature: the single aperture eyes and the compound eyes. Usually, cameras and most of artificial imaging systems are similar the single aperture eyes. But compound lenses can be more compact than single lenses. Our design is based on insect compound eyes, which also have a wide field of view (FOV). With the rise of micro-optical techniques, fabricating compound lenses become easier than before. The simplest structure of a curved microlens array is making microlenses on a parabolic surface. In this paper, we proposed a multi-channel imaging system, which combining the principle of the insect compound eye and the human eye. The optical system enables the reduction of track length of the imaging optics to achieve miniaturization. By the aid of optical engineering software of ZEMAX, the multi-channel structure is simulated by a curved microlens array, and we used Hypergon lens as main lens to simulate the human eye, which can achieve the purpose of the wide FOV. With this architecture, each microlens of a microlens array transmits a segment of the overall FOV. The partial images that are separately recorded in different channels are stitched together to form the final image of the whole FOV by software processing. A 2.9 mm thin imaging system with 59 channels with 76° FOV is optimized using sequential ray tracing of ZEMAX on a 4.8 mm x 3.6 mm image plane.

8842-2, Session 1

Relating transverse ray error and light fields in plenoptic camera images *(Invited Paper)*

Jim Schwiegerling, The Univ. of Arizona (United States); J. Scott Tyo, College of Optical Sciences, The Univ. of Arizona (United States)

Plenoptic cameras have emerged in recent years as a technology for capturing light field data in a single snapshot. A conventional digital camera can be modified with the addition of a lenslet array to create a plenoptic camera. The camera image is focused onto the lenslet array. The lenslet array is placed over the camera sensor such that each lenslet forms an image of the exit pupil onto the sensor. The resultant image is an array of circular exit pupil images, each corresponding to the overlying lenslet. The position of the lenslet encodes the spatial information of the scene, whereas as the sensor pixels encode the angular information for light incident on the lenslet. The 4D light field is therefore described by the 2D spatial information and 2D angular information captured by the plenoptic camera. In aberration theory, the transverse ray error relates the pupil coordinates of a given ray to its deviation from the ideal image point in the image plane and is consequently a 4D function as well. We demonstrate a technique for modifying the traditional transverse ray error equations to recover the 4D light field of a general scene. In the case of a well corrected optical system, this light field is easily related to the depth of various objects in the scene. Finally, the effects of sampling with both the lenslet array and the camera sensor on the 4D light field data are analyzed to illustrate the limitations of such systems.

8842-3, Session 1

Miniaturized optical-fiber endoscope without inertial scan for simultaneous imaging and laser microsurgery

Jost Adam, Univ. of California, Los Angeles (United States) and Christian-Albrechts-Univ. zu Kiel (Germany); Philipp Metz, Martina Gerken, Christian-Albrechts-Univ. zu Kiel (Germany); Bahram Jalali, Univ. of California, Los Angeles (United States) and California NanoSystems Institute (United States)

Minimally invasive procedures as used in colonoscopic, arthroscopic, thoracoscopic or neurologic surgeries benefit from a reduced size of endoscopic devices. Spectrally encoded imaging has been proposed as a way to implement miniaturized endoscopy, as only a small-diameter single fiber is needed. Recently, a single-fiber-based device performing simultaneous confocal microscopy and high-precision laser microsurgery (SECOMM) was demonstrated. SECOMM achieves a 2D spatial dispersion by the use of a virtually imaged phased array (VIPA) spectral disperser, in conjunction with a reflective diffraction grating, creating a one-to-one mapping between spatial coordinates and optical wavelength. In this contribution we propose a highly miniaturized optical design of SECOMM based on a VIPA and a perpendicularly aligned volume holographic grating embedded between two prisms (GRISM). A solid glass VIPA produces several overlapping diffraction patterns at a high angular dispersion (x-direction). These are fanned out in y-direction by the GRISM producing a 2D-angular dispersion often referred to as “spectral shower”. Using an imaging lens the angular dispersion is finally mapped into position space producing a specific field of view. Here, we theoretically investigate the spectral shower in angular units and provide a systematic device parameter analysis for the proposed axial design. A center wavelength of 800 nm is considered for use with a TI:sapphire laser as the light source. However, our endoscope design can also operate at other wavelengths such as visible and infrared. The best system performance is obtained by using a high optical bandwidth combined with a low grating period and a low VIPA tilt.

8842-4, Session 1

Advances in optical design and optimization of miniature zoom optics with liquid lens element

Yi-Chin Fang, National Kaohsiung First Univ. of Science and Technology (Taiwan); Cheng-Mu Tsai, Kun Shan Univ. (Taiwan)

An optical design of 2X optical miniature zoom lens with liquid lens elements and optimization method: discrete lens groups shifts (DLGS) has been presented in this research. Two liquid elements are applied to minimize the overall length of zoom optics. Moreover, a compensative optimization method with assistance of Genetic Algorism is introduced in this research with a new concept of DLGS, which not only solve the complicated problem of liquid optics itself but also improve the performance of optics. Genetic algorithms (GA) written in CODE V plays the role at finding out the appropriate parameters such as curvatures, thicknesses, glass materials and etc. Besides, one table with great lens groups shifts by GA would be created to move the lens groups on the optimal positions of different zooms. As a result, the DLGS optimization method associated with the GA optimization improve the zoom lens performance averagely 40% better than traditional ones.

8842-5, Session 2

On the use of special aperture stops

Wenjing Zhao, Cornelius F. Hahlweg, Hendrik Rothe, Helmut-Schmidt Univ. (Germany)

The use of special aperture stops offers a wide variety of image conditioning and pre- processing possibilities. The mathematical description and modeling of the resulting effects depends on the question whether the illumination is coherent or incoherent, which then leads to fourier-optical or geometrical optical views. The paper is dedicated to a theoretical discussion of the commonalities, in other words the question where the fourier view is to be applied in the non-coherent case. The discussion is inspired by investigations of shadowgraph techniques, which deliver the practical examples as well.

8842-6, Session 2

Rear pupil imaging system for extended depth of field

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Recently, extended depth-of-field, super-resolution and light-field techniques have become more and more important in many digital imaging systems, and those studies can be incorporated into pupil engineering. Pupil engineering modulates the amplitude or phase of pupil position, making the point spread function and modulation transfer function have some advantageous properties. For extended depth of field (DoF), the pupil of system employs wavefront coding mask to engineer the point spread function be insensitive to defocus. Using post processing such as Wiener decoding filter, we can restore the intermediate image with high fidelity. However, pupil engineering cannot suit all optical systems. Since the modulating element affects the performance from different optical positions, such as entrance pupil, exit pupil or aperture stop. Changing these specific positions will change the modulation strength. In this paper, we proposed a best solution called rear pupil imaging system (RPI system) to overcome this issue. Rear pupil imaging system (RPI system) optimizes pupil position at rear position to extend depth of field. It satisfies the linear shift invariant by modulating pupil position while keeps the point spread function to constant. The spot size is dependent on the coding strength, and the coding strength is dependent on the extended ability. RPI system can utilize heavy coding and huge extended ability than other optical systems. The simulation result shows DoF was extended over three times by RPI system than other extended DoF optical systems.

8842-7, Session 2

Special imaging techniques employing polarization, aperture stop, and phase effects

Wenjing Zhao, Carsten Daniel Skaloud, Helmut-Schmidt Univ. (Germany); Cornelius F. Hahlweg, Helmut-Schmidt Univ. (Germany) and bbw Hochschule (Germany); Hendrik Rothe, Helmut-Schmidt Univ. (Germany)

In the paper static and time variant photographic techniques for observations of pressure, density and stress pattern in transparent media are discussed. Special attention is drawn on the observation of dynamic stress effects in extended media under polarized illumination. While a homogeneous stress distribution along the optical axis leads to the well established planar ‘opticon’ configuration, the quantitative observation of 3D distributions might demand the separation of slices or planes along the direction of observation. A typical example is the stress distribution caused by irregular bodies embedded in a block of gleatin. The separation can be realized by intentional strict reduction of depth of field using special aperture stop configurations. In the paper theoretical and practical aspects and especially the fourier-optical vs. geometrical-optical implications of special aperture stops in non-coherent illumination shall be discussed. Various practical examples of quasi-static and short processes are included. A corresponding paper focussing on the vibration pattern in guitars delivers further examples.

8842-8, Session 2

Laser autostereoscopic projection system

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The current autostereoscopic projection system is accomplished by array projectors. It is easy in the optical realization but leading a drawback with size. Another type is to place the shutter on the screen. It saves the volume but reduces the efficiency depending on how many views to be produced. The shutter in the lens aperture has the same efficient problem, too. To overcome these problems, a full HD autostereoscopic projector based on the lens aperture switching type is proposed. It has RGB laser sources and can produce 16-view or even higher stereoscopic image.

This system cancels the shutter in the lens aperture, it is accomplished by the opti-mechanism itself. The specific light on the lens aperture comes from the point on the DMD is reflected to different angles. The proper angle of light is generated in the object side by the relay and folding system. The UHP lamps or the LED are difficult to constrain the rays in a relative small cone angle. For this reason, the laser is applied to the design. The very small etendue of laser is good for this architecture. The rays are combined by dichroic filter from RGB laser sources then forming and expanding to the mirror. The mirror is synchronized with DMD by the DSP control system. The images of different views are generated by DMD and specific position of the mirror. By the double lenticular screen, the lens aperture is imaged to the observer’s viewing zone. The 3D scene is created.

8842-9, Session 2

Transient and spectral analysis of power modulation of light in natural and artificial situations

Cornelius F. Hahlweg, Helmut-Schmidt Univ. (Germany) and bbw Hochschule (Germany); Cornelia Weyer, Norddeutsches Forschungsinstitut e.V. (Germany)

For investigations on the perception and physiological effects of power modulation of light in conjunction with acoustic stimuli – like in entertainment shows - as described in a corresponding paper a reference

device was desirable. So a broadband spectrometer for analysis of the power modulation of light up to several kHz versus the light wavelength of the visual spectrum was designed and tested. Besides the primary intention the gathered multispectral data sets can be used for identification of artificial light components in natural environments. The paper deals with design issues and verification problems and delivers some representative experimental results.

8842-10, Session 3

Energy-minimized design in all-optical networks using unicast/multicast traffic grooming

William S. Puche, Javier E. Sierra, Ferney O. Amaya, Univ. Pontificia Bolivariana (Colombia)

The increased bandwidth required by applications today, tends to raise the amount of optical equipment, for this reason, it is essential to maintain a balance between the wavelength allocation, available capacity, number of optical equipment, such so as to achieve the lowest power consumption Optical green to work with. You could say that we propose a model that minimizes energy consumption, using unicast / multicast traffic grooming in optical networks.

The proposed model will take into account the results consuming and wavelength in an optical network capacity taking into account multiple sessions and which is more effective comparing between unicast and multicast, this ratio having analyzed the various optical components of the network , which will be compared with real devices and display energy consumption which occurs in the network. This allows large research centers or telecommunications companies in the region, determine which model could go to the needs of these and make it a significant energy efficiency and cost savings.

8842-11, Session 3

On modal analysis of coupled non-identical optical gradient waveguides

Nikolai D. Espinosa, Army Polytechnic School (Ecuador); Jesus Vila, Univ. del Pais Vasco (Spain); Tatiana Acosta, Marcelo Urbina, Paola Leon, Christian N. Vega, Army Polytechnic School (Ecuador)

Using a new analytical scalar approximation called modal theory (alpha method) we obtain the numerical analysis of propagation constants and field modes of two non-identical optical waveguides.

The results to be obtained will be valid for arbitrary coupled waveguides as well as for coupled identical waveguides.

Wave mode calculation and plotting will be done under a MatLab® environment, considering different coupling variables for both structures and different distances between the center of the fiber optic cores and plane wave guide.

8842-12, Session 3

ILP model for greenfield WDM PON network design based on physical layer constraints

Germán V. Arévalo, Univ. Politécnica Salesiana (Ecuador); Javier E. Sierra, Univ. Pontificia Bolivariana (Colombia)

The optimal dimensioning of the network is one of the main problems in the design of a WDM PON. Traditionally, the network size is determined by the traffic demand, the user density, the active and passive equipment capacity and some physical restrictions like the attenuation in the optical path. However, the physical layer limitations become more relevant in WDM PON transmissions, specially when employing very high data rates like 10 Gb/s or beyond. In this paper we propose a novel physical-layer-restrictions based integer linear programming (ILP) model for greenfield next generation 10 Gb/s WDM PON network design.

The results of the model are validated by means of the computational results obtained with CPLEX studio - OPL software.

The proposed ILP model takes into account not only the attenuation of the signal in the optical path but also, through the use of the data obtained by the optical systems simulation software OptSim, we take in to account the restrictions imposed by other phenomena like dispersion, cross talk and some non linear effects typically present in a WDM optical transmission.

8842-13, Session 3

Scenario analysis for performance evaluation of free-space quantum and classical communication channels

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In order to asses a free space optical links, using a Cassegrain telescope for both classical (i.e. coherent and direct detection) and quantum (coherent, Dolinar-Kennedy system) several scenarios were analyzed. This analysis was conducted through a software tool that uses some specific parameters imposed by the environmental condition and hardware used, such as: the pointing and tracking errors, turbulence, modulations schemes, and visibility, among others; in order to obtain the general performance parameters of the simulated link, such as: channel capacity, bit error rate, transmission time and the photons number. The tool developed allows the user to produce useful information for either a clearly and precise way to assess possible success of the implementation of the free space optical link, or a way to identify the phenomena that might suggest hardware adjustments to improve the overall performance of the system. Results allow the revision of the expected link performance for quantum key distribution systems; although it is possible to use it for general optical quantum communications systems.

8842-14, Session 3

Evaluation and optimization of the Savitzky-Golay smoothing filter for noise reduction in thin film interference signal analysis

Petros I. Stavroulakis, City Univ. London (United Kingdom) and Sencon (UK) Ltd. (United Kingdom); Panos Liatsis, City Univ. London (United Kingdom); Nicholas Tipping, Paul Craddock, Sencon (UK) Ltd. (United Kingdom)

In this work, we present a comparison between Savitzky-Golay filtering and the traditional treatment of subtracting a dark signal to reduce noise from spectra acquired by a spectrometer in an adaptive thin film thickness measurement system where integration time needs to be varied for each measurement. In detail, it is found that due to the nature of the spectral interference signal, Savitsky-Golay filtering implemented indiscriminately with a static bin size has the potential of reducing the interference fringe height unequally throughout the spectrum. Thus when the period of the fringes is comparable to the bin size, the Savitzky Golay filtered signal results in a 'damped sinusoidal' with the height of the interference fringes steadily increasing with wavelength. The classical dark signal subtraction technique on the other hand does not produce such defects but it is discussed that dark signal removal cannot be easily used as a general-purpose solution for stand-alone adaptive systems (such as those used in industrial applications) because dark signals are spectrometer-dependent and would need to be stored for all of the integration times, since the magnitude of the noise also depends on integration period. Moreover, dark signals should be ideally acquired before a signal is taken, to account for any possible noise drift. Finally, we show that by applying a dynamic and gradual variation of the Savitzky-Golay bin parameters across the signal, the Savitsky-Golay technique can be used as a general-purpose noise reduction technique for thin film interference signals collected by a spectrometer in an adaptive system.

8842-15, Session 4

The unique sound of the Univibe, part II: transient behaviour

Cornelius F. Hahlweg, Helmut-Schmidt Univ. (Germany) and ITB Berlin (Germany); Hendrik Rothe, Helmut-Schmidt Univ. (Germany)

(The paper is intended for the upcoming session on optics and music)

The Univibe is an effect pedal mostly used by electric guitar players. It is based on an opto-electronically controlled all-pass chain. In last year's paper on the subject an idealized system model was derived, which lead to deeper discussion of the musical consequences of the effect in terms of harmonic analysis of single tones and chords in clean and distorted mode. As a direct continuation the present paper now deals with the transient behaviour of the device. The transient response is essential for understanding the special sound character, the reaction on picking techniques and the interaction with certain instruments like the Fender Stratocaster. Therefore the system model is expanded and the pulse response of the idealized time invariant system is derived. Also the classic Strat floating vibrato and pickup configurations are investigated particularly with regard to their correspondence with the Univibe pulse response. The talk will contain the sound examples cited in the paper, as well as practical demonstrations.

8842-16, Session 4

Visualizing sound: music in slow motion

Cornelius F. Hahlweg, Wenijing Zhao, Hendrik Rothe, Helmut-Schmidt Univ. (Germany)

The core of the present paper is derived from recent investigations of high speed photographic techniques using schlieren, cross polarization and other special methods for visualization of material effects as described in a corresponding paper. Here we use high speed video under polarized illumination for dynamic stress analysis over the audible spectrum. As a first example the vibration modes of various body shapes of electric guitars, which were modeled from acrylic glass, are visualized and compared. Further the stress caused by cantilever during reproduction of phonograph records on classic record players is investigated, which leads to the question of record wear and the usefulness of optical record players as discussed in last year's session. The talk will be supported by footage, sound samples and practical demonstrations.

8842-17, Session 4

Perception of power modulation of light in conjunction with acoustic stimulation

Cornelia Weyer, Norddeutsches Forschungsinstitut e.V. (Germany) and G&S Gesundheit und Sicherheit für Betriebe GmbH (Germany); Cornelius F. Hahlweg, Helmut-Schmidt Univ. (Germany) and bbw Hochschule Berlin (Germany); Harald Gercke-Hahn, G&S Gesundheit und Sicherheit für Betriebe GmbH (Germany)

An ongoing study concerning the perception of LF power modulated light in conjunction with acoustic stimulation, as found for instance in music entertainment shows, is discussed. The paper deals with the test device and the study design. The perception of light flicker has been an issue TV and monitor screen design as well in arc welding for decades. As a basis for the intended investigations the cut-off frequency and threshold modulation depth over the peripheral angle are measured for a group of test persons, the physiological effects are monitored using ECG. The results are compared to measures found in literature to validate the test conditions. The test conditions then are extended by acoustic stimuli. While a coherent combination of slow deep light modulation with acoustic pulses of the same frequency is typical for light accompaniment of music – like spot lights and drums being in step – the basic question here is the perception of such coherence near and above the flicker perceptibility. Further the effect of acoustic stimuli at audible harmonics of the flicker and the perceptibility of slight incoherence or detuning are questioned. First results are presented and discussed. The presentation contains practical examples.

8842-18, Session 5

Toleranced freeform optical design with extended sources using ray targeting *(Invited Paper)*

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Freeform optics are limited to design with simplified source models. With a realistic extended source, the resulting design is limited by the ability to hold the source and optic to the desired tolerances. For example, a design is made around the nominal emitter characteristics, such as an encapsulated LED die. This process is called tailoring. Positioning and spectral output can vary appreciably for these emitters. A method to design optics with extended sources with tolerances taken into account is presented. This method uses targeted raytracing to specify particular points on optical surfaces. In the method presented here, the source is represented instead as a collection of non-ideal sources, each weighted according to the statistics of the dimensional and color variations that are expected in the source. The design is iteratively developed over its extent where each step accounts for the tolerances of the multitude of potential ray paths through the optics. The end result is to design optics that are tolerant to the predicted level of error, while maintaining the desired level of efficiency and distribution at the target. This method notably samples the differential étendue aspects of the source as it propagates through the system. Upon solution of the iteratively generated reflector control points, an optimization run can be performed to improve performance. We will present the example applications of mating encapsulated LEDs to secondary optics that incorporate tolerancing of LED die size and placement and LED color variation.

8842-19, Session 5

Characterization of flexoprinting patterns

Lukas Pescoller, Peret GmbH (Italy); Cornelius F. Hahlweg, Helmut-Schmidt Univ. (Germany) and bbw Hochschule Berlin (Germany) and Norddeutsches Forschungsinstitut e.V. (Germany)

In continuation of last year's paper on distorting optics for inspection of 2 1/2D surfaces methods for the characterization and quality control of flexoprinting plates using image processing are discussed. Special attention is drawn to the mottle of the patterns, which is a major quality and responsible for the macroscopic perception of the resulting print product. A fast and rugged method is the interpretation of the density and coherence of the traces of minimum correlation, derived from the auto-correlation function. Mathematics, reliability and scaling problems are discussed, practical examples are included.

8842-20, Session 5

Helical apodizers for tunable hyper Gaussian masks

Jorge Ojeda-Castaneda, Sergio Ledesma, Cristina M. Gomez-Sarabia, Univ. de Guanajuato (Mexico)

For a wide range of applications, it is desirable to engineer the axial impulse response of an optical system. To that end, it is convenient to exploit McCutchen theorem, which relates through a Fourier transformation the axial complex amplitude distribution with the angular average of the generalized pupil function /1-3/.

Here, we apply McCutchen theorem for designing a pair of helically modulated amplitude masks, which work as a pair. By introducing an in-plane rotation, between the elements of the proposed pair, one can control the damping coefficient of any embedded hyper Gaussian apodizers /4/. We show that the proposed optical device is useful for tuning either radially varying masks or annularly varying masks. We analyze the influence of the proposed pair on the axial irradiance distributions, generated by optical systems with extended depth of focus /5/.

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8842-22, Session 6

Designing an acousto-optical spectrometer for Guillermo Haro astrophysical observatory

Alexandre S. Shcherbakov, Adan O. Arellanes, Vahram Chavushyan, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

The Guillermo Haro astrophysical observatory (Mexico) realizes the investigations of galaxies, interstellar medium, and extra-solar planets in the visible and near-infrared range 400 – 1100 nm. Actually, the Boller-Chieves spectrometer is exploited there with mechanically removable optical filters and diffraction gratings with the stroke density 50 – 600 lines/mm of the aperture about 9 x 9 cm and provides the accuracy 9.6 - 0.8 A/pixel. Unfortunately, the required mechanical manipulations, i.e. changing the diffraction gratings with various resolutions and then recalibrating the spectrometer within studying even the same object, are inconvenient and mean wasting rather expensive time for astrophysical observations. This is why exploiting an acousto-optical cell as a dispersive element in that spectrometer is desirable. Potentially, it realizes tuning the spectral resolution and the range of observation electronically, breaking those imperfections down and excluding filters. In this case, the spectrometer's optics collimates light on the mechanically fixed acousto-optical cell. Currently, we consider two crystalline materials for similar cell providing the stroke-density 300 lines/mm along the aperture 9 cm. It is the lithium niobate ($LiNbO_3$)-crystal excited by the longitudinal acoustic mode along the [100]-axis at the frequency 2 GHz, giving total losses ~5.4 dB/aperture. Then, one can take the bismuth germanate ($Bi_{12}GeO_{20}$)-crystal using the shear acoustic mode along the [110]-axis at 0.53 GHz with the losses ~6.3 dB/aperture. The figures of acousto-optical merit for these materials are neighboring and promise efficiencies of operation sufficient for observations. Finally, the proposed acousto-optical spectrometer with the reduced dimensions and weight provides the spectral resolution 5-15 A.

8842-23, Session 6

ESPRESSO APSU: Simplify the life of pupil slicing

Paolo Conconi, Marco Riva, INAF - Osservatorio Astronomico di Brera (Italy); Stefano Cristiani, INAF - Osservatorio Astronomico di Trieste (Italy); Denis Mégevand, Francesco Pepe, Observatory of Geneva (Switzerland); Alexander Cabral Pereira, Univ. de Lisboa (Portugal); Paola Spanó, Filippo M. Zerbi, INAF - Osservatorio Astronomico di Brera (Italy)

This paper presents the Espresso Anamorphic pupil Slicer (APSU) implementation. ESPRESSO, the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, will be installed on ESO's Very Large Telescope (VLT). The light coming from the Telescope through a Coudè Focus of all the Four Telescope Units (UTs) will be collected by the Front End Unit that provides Field and Pupil stabilization and injects the beams into the Spectrograph fibers. The light is projected into the spectrograph through a bungle of fibers.

In this work we will present the design and trade off for the pupil slicing system introduced in order to increase the resolving power, effectively decreasing slit width. It's based onto simplified optical component that introduce large anamorphism while keeping low aberrations by means of cylindrical optics. We describe here the trade off between slicing through two adjacent squared doublets and two achromatic prisms. The opto-mechanical performance are here presented and described. The slicer mirror stack in the spectrograph focal plane is composed of four cylinder mirrors (curvature in the local YZ-planes) mounted together, aligned, and fixed. Trade-off between cylinder and flat mini-mirror are descirbed evaluating manufacturability and costs Vs performances

8842-24, Session 6

Novel optical technique to measure sub-pixel responsivity of various imaging sensors

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Effective pixel area measurement of various CCD and CMOS imaging sensors is an important activity for flight model camera payload design in various remote sensing satellites. Knowledge of active pixel area and two dimensional responsivity profiles enables the system designer to decide upon optical parameters for achieving diffraction limited performance from integrated camera payload. We have designed and developed a test setup to generate circular light spot of 4µm at wavelength range from 400nm to 1100nm and to perform two dimensional pixel scan of various CCD & CMOS sensors. This paper describes optical system design aspects, final opto-mechanical configuration, test results carried out on 1Kx1K frame transfer CCD having pixel dimension 13µmx13µm and the capabilities of test setup apart other than pixel area measurement.

8842-25, Session 6

Range reconstruction model for 3D gated imaging

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Range gated imaging is a remote sensing acquisition which involves the emission of laser pulse and an intensified camera to gate the reflected laser pulse. Range accuracy has always been an issue especially when highly accurate reconstructed model is expected as the final outcome. The reflected pulse profile and pulse instability are among the issues that affected the range accuracy where general solution such as constant offset is not applicable. In this paper, a study to estimate a more accurate model for the reflected pulse profile has been carried through experiments. T Location-Scale model has been proposed to replace the Gaussian model as the general assumption for range-gated image formation model. The improvement on range accuracy which is around 0.3% has been verified through simulation based on the acquired samples. The series of range-gated images can be reconstructed into three-dimensional through range calculation. The accuracy of the three-dimensional model has been proven to be affected by the number of gated images used in the reconstruction.

8842-26, Session 7

Stereo-matching image-processing by selected finite length edge line-matching on least square method

Akira Akiyama, Kanazawa Technical College (Japan); Nobuaki Kobayashi, Kanazawa Institute of Technology (Japan); Eiichiro Mutoh, The Society of Japanese Aerospace Companies (Japan); Hideo Kumagai, Tamagawa Seiki Co., Ltd. (Japan)

We have studied the stereo matching image processing by selected finite length edge line matching on least square method for ranging the object and image recognition.

The two images from a pair of the stereo imagers may have some image deformation each other with the rotation, expansion and contraction of edge line. To make a flexible stereo matching we construct the finite length edge line as a simple standard and search the similar edge line segment in another image.

The construction of the selected finite length edge line as a standard follows the next 5 steps. The first is blocking the binary auto focused high pass filter image by Daubechies wavelet transformation. The second is thinning each blocked image by Hilditch thinning method. The third is tracing each thinned edge line by clockwise or counterclockwise direction and making the sequential edge line. The forth is applying the least square regression analysis of the first order polynomial on finite pixel length edge line on each point of edge line and evaluating the regression error by standard deviation and inclination of edge line. The last is selecting the part of edge line having the appropriate least square regression property.

Selected finite length edge line matching is evaluated by the root mean square computation of the difference between two edge lines under coinciding two start pixel points and the inclination value of two regression lines. From this evaluation we made the flexible and reasonable edge line stereo matching. And it is possible to compute the range information and realize the shape of object edge. To make good quality image captures for the current processing, a pair of imagers are equipped with controllable aperture mechanism.

8842-27, Session 7

A monochromatic recursive convolution finite-difference time-domain algorithm and its application in simulation of arrays of metal nano-particles

Saswatee Banerjee, Sumitomo Chemical Co., Ltd. (Japan)

A special class of finite-difference time-domain (FDTD) algorithm, called recursive convolution (RC) FDTD, is developed to simulate metals in visible domain [1]. Conventionally, RC-FDTD is implemented for pulsed light sources. This requires that the analytical model of permittivity should fit the handbook permittivities (derived from experimental measurements) closely over broadband of wavelengths. This is not an easy task and the choice of a particular model depends on the metal being simulated.

We developed a monochromatic version of RC-FDTD [2]. This algorithm uses the 1st order Drude model [1] to evaluate the convolution operation needed to make FDTD stable for metals for which the real part of permittivity is negative. Unlike the conventional RC-FDTD, the Drude parameters are computed at each wavelength of the incident light using the corresponding handbook value of permittivity. Hence, this version of RC-FDTD allows us to use the handbook permittivity values at all wavelengths of operation.

Here, we study the dependence of localized surface plasmon resonance (LSPR) properties of arrays of nano-particles on the shape, size and number of particles in the array and the interparticle distance [3]. We compute the extinction spectra of linear nano-particle arrays using the RC-FDTD method. For such arrays, the peak of the extinction spectra shifts toward the longer wavelengths as the interparticle distance decreases.

References

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8842-28, Session 7

Modelization of the whispering gallery mode in microdisk and microgear resonators using a toeplitz matrix formalism for single-photon source

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The work presented in this paper develops a new formalism to design a microdisks and microgears structures. The main objective is to study the optic geometric parameters influence on the microdisks and microgears structures resonance behavior. This study is conducted to choice a resonance structure with height quality factor Q to be associated with Quantum dot to form a single photon source. This new method aims to design resonant structures are simpler and requires less computing performances than FDTD and Floquet Block methods. This formalism is based on simplifying Fourier transformed and using toeplitz matrix writing. This new writing allows designing all kind of resonance structures with any defect and any modification. In other study we have design a quantum dot emitting a photon at 1550 nm of the fundamental mode, but the quantum dot emits other photons at other wavelengths. The focus of the resonant structure and the quantum dot association is the resonance of the photon at 1550 nm and the elimination of all other photons with others energies. In this paper we design a GaAS microdisk and microgear and we compare the quality factor Q of this two structure and we conclude that the microgear is more appropriated to be associate to the quantum dot and increase the probability P1 to obtain a single photon source at 1550 nm and promotes the obtaining of single photon. The performance improving of the resonant structure is able to increase the success of quantum applications such as quantum gates based on single photon source.

8843-1, Session 1

Determination of angular momentum content in partially coherent beams through cross correlation measurements

Adad Yepiz Escalante, Benjamin Perez-Garcia, Raul I. Hernandez-Aranda, Tecnológico de Monterrey (Mexico); Grover A. Swartzlander Jr., Rochester Institute of Technology (United States)

A means to measure orbital angular momentum in a partially coherent beam is demonstrated by using a wavefront folding interferometer. This interferometer allows us to study the cross correlation function of a partially coherent vortex beam. It is shown that the cross correlation function possesses ring dislocations which are related to the topological charge of the partially coherent vortex, exhibiting a one to one correspondence between the number of rings and the value of the topological charge, thus providing a direct measure of the orbital angular momentum.

8843-2, Session 1

Measuring topological charge using Stokes parameters

Benjamin Perez-Garcia, Dorilian Lopez-Mago, Adad Yepiz Escalante, Raul I. Hernandez-Aranda, Julio C. Gutiérrez-Vega, Tecnológico de Monterrey (Mexico)

An alternative method to experimentally measure the topological charge of a vortex beam is presented. The method is based on the number of polarization singularities arising in the superposition of two off-axis Laguerre-Gauss beams having orthogonal polarizations. The experimental setup consists of a modified Mach-Zehnder interferometer which provides control over the polarization structure by allowing us to introduce lateral displacements as well as relative phase variations between the two arms of the interferometer. A comparison between theoretical and experimental results is done with very good agreement. This method offers an alternative for measuring orbital angular momentum content in a beam without the need of interfering with a reference plane wave. The dynamics of polarization singularities are also studied experimentally.

8843-3, Session 1

Optical fields with tunable transverse intensity fluxes arranged over a semi-circle

Adrian Ruelas, Manuel G. Jurado-Taracena, Julio C. Gutiérrez-Vega, Tecnológico de Monterrey (Mexico)

Accelerating and Airy beams are of great interest as they remain diffraction free while experiencing a quadratic shift along propagation, transporting intensity in the transverse plane over a straight line. This work presents optical fields that transport intensity in the transverse plane over a continuum of directions arranged over a semi-circle, having the possibility of controlling both the angular distributions of relative intensity and spatial frequency. We construct these beams via a superposition of plane waves with distinct longitudinal and transverse wavevector components, forming periodic and quasi-periodic intensity profiles along propagation. The on-demand light patterns presented here are expected to find applications in optical trapping as Airy beams and nondiffracting beams have previously found.

8843-4, Session 1

Generating and analyzing non-diffracting vector vortex beams

Yanming Li, North Carolina State Univ. (United States); Angela Dudley, Thandeka I. Mhlanga, CSIR National Laser Ctr. (South Africa); Michael J. Escuti, North Carolina State Univ. (United States); Andrew Forbes, CSIR National Laser Ctr. (South Africa)

We report the first experimental generation and analysis of non-diffracting vector vertex beams by using a Spatial Light Modulator (SLM) and an azimuthal birefringent plate (q-plate). The SLM generates scalar Bessel beams and the q-plate converts them to vector vortex beams. Both single order Bessel beam and superposition cases are studied. The polarization and the azimuthal modes of the generated beams are analyzed. We examine the azimuthally varying polarization by recording the beam profile through an analyzer. We measure the orbital angular momentum (OAM) of each polarization component by doing a modal decomposition on the beams separated by a linear and a circular polarization beam splitter. The results are in good agreement with theory, showing different OAM in orthogonal circular polarizations and the corresponding OAM superposition in linear polarizations. The full analysis concludes that our generated beams have cylindrical polarization and carry polarization dependent orbital angular momentum.

8843-5, Session 1

Techniques to sort Bessel beams *(Invited Paper)*

Angela Dudley, Thandeka I. Mhlanga, Andre McDonald, CSIR National Laser Ctr. (South Africa); Martin P. Lavery, Univ. of Glasgow (United Kingdom); Filippus S. Roux, CSIR National Laser Ctr. (South Africa); Miles J. Padgett, Univ. of Glasgow (United Kingdom); Andrew Forbes, CSIR National Laser Ctr. (South Africa)

In this work we will present two techniques for the measurement of superimposed higher-order Bessel beams. In the first technique we will outline a simple approach using only a spatial light modulator and a Fourier transforming lens to decompose the OAM spectrum of an optical field. We test this approach on symmetric and non-symmetric superpositions of non-diffracting higher-order Bessel beams. Our second procedure consists of two refractive optical elements which perform a Cartesian to log-polar coordinate transformation, translating helically phased beams into a transverse phase gradient. By introducing two cylindrical lenses we can focus each of the azimuthal modes associated with each Bessel beam to a different lateral position in the Fourier plane, while separating the radial wave-vectors in the image-plane.

8843-6, Session 2

Beam shaping by volume phase structures in photo-thermo-refractive glass *(Invited Paper)*

Marc SeGall, Daniel Ott, Ivan B. Divliansky, Julien Lumeau, Sergiy Mokhov, Boris Y. Zeldovich, Leonid Glebov, Univ. of Central Florida (United States)

Multiple applications of lasers require various forms of beam shaping for optimal use. This may take to form of aberration reduction, mode conversion, etc. Conventionally these shapers are produced by phase masks which utilize spatial profiling of the surface of an optic. Here we demonstrate phase masks which are recorded in the volume of photo-thermo-refractive (PTR) glass. PTR glass is a photosensitive glass which provides refractive index change of up to 10^-3 after exposure to near

UV radiation followed by thermal development. Due to its low absorption and high damage threshold it is well suited for many laser systems including high power systems. This material has been successfully utilized previously for the holographic recording of volume diffractive elements (volume Bragg gratings), which have been used in applications for spectral and angular narrowing, coherent and spectral beam combining, and the stretching and compression of laser pulses. To record phase masks in PTR glass we expose the glass to UV radiation which has been transmitted through binary amplitude masks. These may be used to produce binary phase masks or grayscale phase masks depending on the profile of the amplitude mask. Volume phase masks have been used to generate Fresnel lenses of varying focal lengths, convert Gaussian beams to higher order Hermite-Gauss and Laguerre-Gauss modes, to produce optical vortices whose topological charge is controlled by the total phase incurred, and to produce aberration-correcting elements.

8843-7, Session 2

The effect of SLM dependent dispersion on spatial beam shaping

Dirk-Mathys Spangenberg, Stellenbosch Univ. (South Africa); Angela Dudley, CSIR National Laser Ctr. (South Africa); Andrew Forbes, CSIR National Laser Ctr. (South Africa) and Univ. of KwaZulu-Natal (South Africa)

Spatial light modulators (SLM) used for spatial modulation of lasers are often used in conjunction with very narrow bandwidth laser light where diffractive dispersion could be approximated as a constant. It is known that diffractive dispersion is inversely proportional to wavelength and this effect can be compensated for depending on the optical set-up. SLMs use birefringent liquid crystal (LC) pixels each with adjustable refractive index at a specific polarization. The range of the adjustable refractive index is wavelength dependent. This adds an additional SLM dependent dispersion. Note that we distinguish between diffractive dispersion and SLM dependent dispersion. SLMs are therefore calibrated in order to have linearly adjustable phase retardation of light incident on the pixels between zero and two pi for a specific wavelength. It is therefore unavoidable when using the same SLM, to do beam shaping of a source which emits multiple wavelengths or a wide bandwidth, that the device will not modulate all wavelengths between zero and two pi. We numerically and experimentally investigate the effect of SLM dependent dispersion on spatial modulation of light incident on a 2D SLM. We further discuss why it is possible to modulate multiple wavelengths between zero and two pi despite SLM dependent dispersion.

8843-8, Session 2

Generation of high-order Bessel beams using an axicon zoom system

Carlos López-Mariscal, U.S. Naval Research Lab. (United States); Fred M. Dickey, FMD Consulting LLC (United States)

We present a novel optical system capable of producing scalable Bessel beams. The system is composed of two positive axicons - which produce the characteristic annular spectrum of Bessel beams -, and a spiral phase plate, which imprints the respective azimuthal phase modulation. The axicon pair and lens are configured as a zoom lens system that provides the scalability in the spectrum. A brief analysis of the system's operation is presented along with design examples and computational simulation of the system's performance.

8843-9, Session 2

Steerable diffraction limited line illumination system using deformable mirror

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Many scientific and industrial applications often require high performance optical systems utilizing spatially shaped illumination patterns of laser beams. Precisely shaped line illumination can be used for various line scanning systems or surface inspection devices. In order to achieve the highest resolution or superior signal to noise ratio limited by the fundamental theory, a diffraction limited illumination optical system (e.g. > 0.7 Strehl ratio) gives the narrowest illumination line width determined by the system's NA (Numerical Aperture) value. For high precision and in-factory industrial applications, the Diffraction Limited Line Illumination (DLLI) needs to be controlled in three dimensional space rapidly as the target object under the illumination may not always aligned with respect to the illumination system. A steerable DLLI system with three degrees of freedom (i.e. axial displacement, rotation, and tilt) is developed using an adaptive optics system. By electronically controlling the Zernike based surface shapes of the deformable mirror, the DLLI in free space is actively positioned and oriented with high accuracy and precision within ~10 milliseconds time scale. The geometrical optics based mathematical model to control the Zernike modes of the deformable mirror and the performance of a bench-top proof-of-concept system will be presented with experimental data and analysis results.

8843-10, Session 2

A measurement system of large size laser beam intensity temporal-spatial distribution based on CCD diffuse transmission imaging

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Laser intensity temporal-spatial distribution means laser beam spatial profile vs. time, through which we can get the nonuniformity, centroid, centroid jitter and beam quality of the laser beam. So it is particularly important to diagnose and evaluate the performance of laser system. We design a measurement system to measure large size laser beam intensity distribution based on CCD diffuse transmission imaging. The measurement principle of the system is presented. The configuration of the measurement system is summarized. There is a highlighting information on the design of diffuse target. The methods of spot geometry distortion rectifying and nonuniformity rectifying are detailedly described. The correction method of the laser spot geometry distortion based on uniting pixels is detailed, by which a mapping is set up between sampling unites and CCD pixels; uniform light source is used to correct the nonuniformity of the responses of the unites. After correction, we can get the exact laser spot. The test results are given, which validate correctness of the method. It provides a new way to measure large size laser profile. The design can measure two laser beam of different wavelength at the same time. The method can provide profile quantitative measurement with high resolution and laser power measurement with high accuracy, which is of great significance for practical engineering applications.

8843-12, Session 3

Beam shaping to generate uniform "laser light sheet" and linear laser spots

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Generation of "Laser Light Sheet" beams and linear laser spots

characterized by uniform irradiance distribution is important in various laser techniques like Particle Image Velocimetry (PIV), Laser-Induced Fluorescence (LIF), hardening, annealing, cladding, uniform laser illumination of linear spatial light modulators. This task can be successfully solved with using refractive beam shaping optics of field mapping type in combination with additional optical components. Due to their unique features: low output divergence, high transmittance, flatness of output phase front and irradiance profile, as well as extended depth of field, the refractive field mappers provide freedom in further manipulation of intensity profile and shape of output beam. Typically design of refractive field mapping beam shapers has circular symmetry; therefore to create linear spot shapes it is suggested to apply anamorphic optical components like cylinder lenses, prism pairs, etc. The combined beam shaping systems allow achieving very high aspect ratio, up to 1:1000, of linear spots with simultaneous providing extended depth of field, i.e. it is possible to realize a “Laser Light Sheet” characterized by keeping uniform intensity of linear spot over extended distance along optical axis.

This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts for creating linear laser spots and “Laser Light Sheet”. Examples of real implementations will be presented as well.

8843-13, Session 3

Active optical system for laser materials processing

Oliver Pütsch, André Temmler, RWTH Aachen (Germany); Peter Loosen, RWTH Aachen (Germany) and Fraunhofer-Institut für Lasertechnik (Germany)

Laser materials processing applications increasingly take full advantage of the utilization of active optical systems. Beside better process efficiency due to improved energy coupling the targeted, dynamic variation of the intensity distribution within the working zone facilitates the development of new methods and techniques for laser materials processing. A totally new approach for the structuring of metallic surfaces is the utilization of laser radiation for structuring by remelting. In contrast to the established techniques, no material is removed but reallocated by the active control of the phase transition of the melt pool. The fabrication of custom textures takes full advantage of this new approach as it facilitates the quick generation and the processing of extended topographies along with reduced production time. Structuring by laser remelting demands the active variation of optical properties since it requires the sophisticated modulation of the laser energy within the working zone. An increased number of degrees of freedom have to be changed during process runtime what makes the optical system design most challenging. An optical set-up has been developed that enables the superposition of cw and pulsed laser beams in the working zone. Piezoelectric driven mirrors allow for the deflection of the laser spots of several microns within the dynamic range of kilohertz. The cw beam is splitted into two shares of intensity that are actively attenuated by retardation plates and polarization coupling. A maximum degree of flexibility is gained by the integration of three tailored zoom-telescopes to vary the spot sizes.

8843-14, Session 3

Dynamic holography for extended object beam shaping

Abbie T. Watnik, Paul S. Lebow, U.S. Naval Research Lab. (United States)

We describe a laboratory experiment to improve the energy-on-target for an extended object. A 532 nm laser beam illuminates a wide area. The initial low-signal return from the target is detected in an off-axis holographic arrangement. The target phase recovered from the hologram is imprinted on an SLM to reshape the beam for the next laser pulse. With each iteration, the gain is increased as more light hits the intended target. We have developed a technique to modify the SLM phase to prevent oversharpening of glints and other high intensity return signal points that cause the beam to collapse to a single point with further iterations. We present laboratory results to verify this approach and demonstrate the increased gain resulting from this dynamic beam-shaping.

8843-15, Session 3

Analysis of the wavefront distortion in the transparent conductive film pockels cell

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Transparent Conductive Film Pockels Cell(TCFPC) contains an electro-optical crystal and two sapphire substrates deposited with conductive film. Passing through one sapphire substrate, the electro-optical crystal, and another sapphire substrate, the distortion of the wavefront occurs. Theoretically, two sapphire substrates coated with conductive film make uniform electric field distribution, however, the uniformity of the electric field is influenced by the unevenness of the surface. In addition, the phase modulation become uneven when the surface of the electro-optic crystal in the uniform electric field is uneven. In this paper, we analyze the relationship between the electric field and the substrate. Simulations are conducted on the distortion of the wavefront by the electro-optic crystal profile to provide theoretical basis for processing sapphire substrate and electro-optic crystal.

8843-16, Session 4

Beam shaping unit for micromachining *(Invited Paper)*

Alexander V. Laskin, AdlOptica Optical Systems GmbH (Germany); Nerijus Šiaulys, ALTECHNA Co. Ltd. (Lithuania); Gintas Šlekys, ALTECHNA R&D Ltd. (Lithuania); Vadim Laskin, AdlOptica Optical Systems GmbH (Germany)

Uniform irradiance distribution of laser spot is highly advisable in various micromachining techniques like scribing, PCB and Through-Silicon Via (TSV) drilling, repair techniques in display making technologies. Scanning over whole working field with using popular 2- and 3-axis galvo mirror scanners is another important part of microprocessing systems. Therefore, combining of beam shaping optics, converting Gaussian to flattop (uniform) laser beam profile, with scanning optical heads is an insistent technical task. To provide flattop irradiance profile it is suggested to apply field mapping refractive beam shaping optics piShaper being characterized by some important features: low output divergence, high transmittance, extended depth of field, capability to work with TEM00 and multimode lasers, as result providing a freedom in building various optical systems. De-magnifying of flattop laser beam can be realized with using imaging technique; the imaging optical system to be composed from F-theta lens of scanning head and additional collimating system to be used right after a piShaper. One of the problems in this approach is implementation of compact design of the collimating part. As a solution it is suggested to apply a specially designed Beam Shaping Unit (BSU) to be installed between a laser and a scanning head and providing: conversion from Gaussian to flattop laser beam irradiance profile, compact collimator design, and functions of laser beam adjustment and adaptation to a laser and a scanning head used in particular equipment. There will be considered design features of refractive beam shapers piShaper and BSU, examples of optical layouts to generate flattop laser spots, which sizes span from several tens of microns to millimetres. Examples of real implementations and results of material processing will be presented as well.

8843-17, Session 4

Beam-shaping-diffuser-based fiber injection for increasing stability of industrial robotic laser applications

Todd Lizotte, Hitachi Via Mechanics (USA), Inc. (United States); Fred M. Dickey, FMD Consulting LLC (United States)

This paper documents the investigation of a diffuser based fiber injection system and its successful implementation into a robotic industrial process used within the automotive industry. This is a new concept based on the idea that a diffuser that has the angular radiation pattern matching the NA of the fiber can be used to approximate the field pattern at the face of a mode filled fiber. The research considered two approaches to this problem. The two related approaches to the problem were developed conceptually and analytically. The first is an implementation that would consist of illuminating the diffuser with a uniform spot having the same shape as the fiber core and imaging the illuminated spot onto the fiber face. The other approach is the use of a far-field (Fourier transform) diffractive element with a transform lens. This paper will provide an overview of the analytics and testing for the two concepts and the final implementation of the design into a square core fiber optical beam delivery system. Further detail will be shared with the performance of the design when integrated within a multi-axis robotic arm, which has six degrees of freedom. These results will include how the fiber injection system improved laser beam stability during process operations, in comparison to traditional simple lens injection methods.

8843-18, Session 4

Laser beam characterization with digital holograms

Andrew Forbes, CSIR National Laser Ctr. (South Africa); Christian Schulze, Daniel Flamm, Friedrich-Schiller-Univ. Jena (Germany); Angela Dudley, CSIR National Laser Ctr. (South Africa); Michael Duparré, Friedrich-Schiller-Univ. Jena (Germany)

We show how laser beam characterization may be done in real-time with digital holograms. We illustrate the power of the techniques by applying them to a variety of laser sources, from fibers to solid-state.

8843-19, Session 4

Customized intracavity generation of high-order mode Laguerre-Gaussian beams with graded-phase mirrors

Lizhi Dong, Ping Yang, Wenjin Liu, Hu Yan, Shuai Wang, Bing Xu, Institute of Optics and Electronics (China)

High-order mode Laguerre-Gaussian (LG) beams are characterized by phase singularity, orbital angular momentum, and larger mode volumes, thus they have attracted a great deal of attentions in both optical and physical communities and are considered as the solutions of certain technological problems. These beams are traditionally formed with extracavity beam shaping techniques with computer generated holograms or spatial light modulator. In recent years intracavity generation of high-order mode LG beams are proposed for higher efficiency and output power through altering the optical pump distribution, inserting absorbing wires and modifying the reflectivity of the output coupler. We present intracavity formation of high order mode LG beams with customized intensity and phase profiles using phase graded mirrors. Although phase-graded mirrors were originally proposed for generating fundamental mode beams with super-Gaussian profiles, we prove that they can also be used to form high-order mode LG beams. In this paper we first introduce the principles of this approach. Then we calculated the first several eigenmodes of the resonator containing the designed phase graded mirror using a 2-D matrix method, and found that the mirror could effectively make the desired field distribution as the fundamental mode of the laser cavity with sufficient mode discriminations. After that we give examples of generating LG beams of several different high-order modes with customized field distributions. In all these cases the designed GPM could effectively form the desired beams. At last we analyze the effects of some perturbations including misalignment, decenter, cavity length variation and imperfection of the graded-phase mirror, and the proper tolerances are discussed.

8843-21, Session 4

Coherent combining of four 100W slab lasers with high beam quality

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Coherent beam combination (CBC) is an effective way to improve the output power and beam quality of laser system. In this paper, we report a coherent combining of four slab lasers with total output power of 400W. Long strip slab laser beam is shaping into square beam using special beam expander which could remove the enormous astigmatism aberration caused by thermal distortion of the slab amplifier. Up to 85% fill factor is achieved by two-dimensional splicing system with small splicing gap. Compact optical system with high sampling frequency is designed to detect the optical axis of four slab lasers. Fast steering mirror (FSM) system driven by piezoelectric ceramics is applied to stabilize four laser beams. When the FSM system is working, the root mean square error of the optical axis is significantly reduced to be less than 2 microradians. The piston phase of four lasers is locked by a fast dithering system based on FPGA using stochastic parallel gradient descent algorithm. When the phase is locked, the peak intensity of the farfield spot under long exposure is increased by 3.8 times, reaching 95% of the ideal case. Thanks to the CBC system the beam quality is improved remarkably, and BQ of the combined laser beam is as good as 1.26. More than 50% of the total energy is locked into the main slob when the phase lock system is on close loop. The experimental results suggest that higher energy CBC could be achieved using the technology presented here.

8843-29, Session 4

A novel interpretation of the integrator

Andrew Stockham, LightWorks Optical Systems (United States)

This paper presents what the author hopes will be a novel interpretation of the integrator, and draws unique comparisons between two types of integrator: the microlens array based imaging beam integrator and the integrating tube, or light pipe, for which a quality factor has been derived.

8843-22, Session PMon

Differential time delay line network for optical controlled beam forming

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Due to the restriction of the aperture effect and the aperture transverse delay, it is very difficult to get large instantaneous bandwidth under wide scan range for a conventional phased array radar. Optical controlled beam forming network (OCBFN) technology can solve this problem. The key of the OCBFN is the optical true time delay line network. In this

paper, we proposed a new differential time delay line network based on the free-space integrated prism array technology. The new method can realize any linear time delay for the space multi-beam radar. Furthermore, the time delay can be adjusted very easily. In order to validate the new method, we design a 4*4 differential time delay line network whose the time delay range is from 0ps to 100ps.

8843-23, Session PMon

Formation and propagation of Bessel beams: practical considerations

Michael Soskind, West Windsor-Plainsboro High School South (United States); Rose Soskind, Rutgers, The State Univ. of New Jersey (United States); Yakov G. Soskind, DHPC Technologies (United States)

Bessel beams belong to a class of propagation invariant, structured beams, and are used in various applications, including particle micro-manipulation, optical coherence tomography, optical metrology, and high resolution microscopy. In practice, Bessel beams are based on the interaction of optical fields with finite lateral dimensions produced by finite aperture optical components, such as axicons.

In this paper, we discuss the formation and propagation characteristics of Bessel beams based on various input field distributions, including Gaussian, vortex, and flat-top fields of finite lateral dimensions. We present the influence of beam forming optics imperfections and component misalignments on the shape of the resulting Bessel beams. We also explore the influence of input field apodization on the properties of Bessel beams. Our results demonstrate that even modest apodization levels of the input field distributions can significantly reduce undesirable axial intensity oscillations in the resulting Bessel beams.

8843-24, Session PMon

Producing Bessel beams based on incoherent superposition of laser fields

Michael Soskind, West Windsor-Plainsboro High School South (United States); Rose Soskind, Rutgers, The State Univ. of New Jersey (United States); Yakov Soskind, DHPC Technologies (United States)

Bessel beams are employed in various applications, including particle micro-manipulation, optical coherence tomography, optical metrology, and high resolution microscopy. Bessel beams are formed from the interaction of optical fields with finite lateral dimensions produced by finite aperture optical components, such as axicons.

In this paper, we discuss the formation and propagation characteristics of Bessel beams based on input field distributions defined by Laguerre-Gaussian beams of different orders. We present the influence of the beam order on the shape and the axial intensity distribution of the resulting Bessel beams. One of the limiting factors in the applications of Bessel beams is related to the variations in the axial intensity distribution of the produced beams. We show that incoherent superposition of input Laguerre-Gaussian beams of different orders can resolve the above limitation and produce Bessel beams with uniform peak intensity distributions over an extended axial distance.

8843-25, Session PMon

Diffracted fields by slit-shape transmittance curves

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The transmittance curves describing effects important in the behavior of the diffracted fields generated by coherent illumination. However, when is realized a spatial transform of the transmittance curve, this can be done by rotating the screen, for example a circle curve, the projection is an ellipse and the diffraction field is no more a soft transformation. In this case, the boundary condition may generate regions identified as singularities regions. In this study, we describe slit- shape transmittance curve whose diffraction field presented bifurcation effects and focusing regions know as caustics. The geometric shape of the transmittance curve allow us to study the structure diffraction fields, they are organized around focusing regions. We describe singularities that correspond to fold and cusped regions, which it is associating to the curvature of the transmittance curve. In the cusp catastrophe is generated the dislocations of the Pearcey diffraction pattern. The generation of singularities is studied by the propagation in free space.

8843-26, Session PMon

Creation of Flattop Light Field through Tightly Focusing of Cylindrical Vector Beams

Maojin Yun, Chenglong You, Mei Wang, Wei Lv, Wenxin Wang, Qingdao Univ. (China)

Recently, the particular polarization distributions of cylindrical vector beams have attracted great attention and quickly became the subject of extensive worldwide research due to their applications in lithography, optical storage, microscopy and optical trapping. In this paper, inhomogeneous status of polarization was obtained by designing the polarization-selective diffractive optical elements. With the optimization by custom-designed merit function and genetic algorithm, long focal depth and smaller focal spot is obtained by the numerical analysis. Meanwhile, 1D, 2D and 3D flat-top light field is designed and discussed. Finally, the property of various pattern cylindrical vector beams is studied. By adjusting the combination of different polarized beams, the optical bubbles and optical cages is obtained by high-NA lens.

8843-27, Session PMon

Optical tweezers formed by pure phase pupil filter

Maojin Yun, Wei Lv, Chenglong You, Qingdao Univ. (China); Mei Wang, Qingdao Univ (China)

Sharply focused light spot have attracted great attention and quickly became the subject of extensive worldwide research due to their applications in lithography, optical storage, microscopy, material processing, and optical trapping. Focusing properties of the radially polarized beam in high numerical aperture system with designed pure phase filter are analyzed in detail by using vector Debye diffraction theory. The simulation result shows that sharper focused light spot and flattop focusing can be obtained with the optimized pure phase filter. And the relation between the side lobes and the designed pure phase filter is also discussed. It is shown that the influence of the side lobes is smaller with the increased number of ring-zones of the pure phase filter.

8843-28, Session PMon

Learning algorithm convergence when utilizing a combined time-frequency representation as a basis

Attie Hendriks, CSIR National Laser Ctr. (South Africa) and Stellenbosch Univ. (South Africa); Hermann Uys, CSIR National Laser Ctr. (South Africa); Anton du Plessis, Christine Margarete Steenkamp, Stellenbosch Univ. (South Africa); Andre Smit, Lourens Rasmus Botha, CSIR National Laser Ctr. (South Africa)

Light is capable of directly manipulating and probing molecular dynamics at its most fundamental level. One versatile approach to influencing such dynamics exploits temporally shaped femtosecond laser pulses. Oftentimes the conditions necessary to induce a desired reaction cannot be determined theoretically a priori. However under certain circumstances these conditions or control mechanisms can be extracted experimentally through trial and error. This can be implemented systematically by using an evolutionary learning algorithm with closed loop feedback. Most frequently pulse shaping algorithms operate within either the time or frequency domain, however seldom both. The choice of basis influences the physical insight gained, as well as the time to convergence of the algorithm.

As an alternative to the Fourier domain, we make use of a combined time-frequency representation known as the von Neumann basis, observing temporal and spectral effects at the same time. We report on the experimental results obtained using the von Neumann basis by optimizing second harmonic generation in a non-linear crystal. We show experimentally that the von Neumann representation converges faster than the Fourier domain when compared to searches in the Fourier domain with the basis sets of the same size. We also report on theoretical results optimizing excitation of vibrational levels in molecular ensembles. Here once again the von Neumann representation converges faster that the Fourier domain.

This report shows that the von Neumann basis can be used as a viable alternative to the Fourier domain with improved convergence time and potentially deeper physical insight.

Conference 8844: Optical System Alignment, Tolerancing, and Verification VII

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8844-1, Session 1

Optomechanical considerations for realistic tolerancing

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Optical tolerancing simulation has improved such that the modeling of opto-mechanical accuracy can better predict end results. One refinement being proposed within this paper is monitor formal interference fits and to check lens elements within their mechanical housings. Without proper checks, simulations may become physically unrealizable and pessimistic, and result in lower simulated yields. This improved simulation method has been defined and demonstrated against with a system without barrel constraints showing the possible difference in yield results. Considerations of the opto-mechanical system will assist in controlling cost and provide more accurate simulation results.

8844-2, Session 1

Alignment of 4-mirror wide field corrector for the Hobby-Eberly Telescope *(Invited Paper)*

Chang Jin Oh, Eric H. Frater, Laura E. Coyle, Matthew B. Dubin, Andrew E. Lowman, Chunyu Zhao, James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States)

The Hobby-Eberly Telescope (HET) Wide Field Corrector (WFC) is a four-mirror optical system which corrects for aberrations from the 10-m segmented spherical primary mirror. The WFC mirror alignments must meet particularly tight tolerances for the system to meet performance requirements. The system uses 1-m class highly aspheric mirrors, which precludes conventional alignment methods. For the WFC system alignment a "center reference fixture" has been used as the reference for each mirror's vertex and optical axis. The center reference fixtures have both a CGH and sphere mounted retroreflector (SMR) nests. The CGH is aligned to the mirror's optical axis to provide a reference for mirror decenter and tilt. The vertex of each mirror is registered to the SMR nests on the center reference fixtures using a laser tracker. The spacing between the mirror vertices is measured during the system alignment using these SMR nest locations to determine the vertex locations. In this paper we present the procedures and results from creating and characterizing these center reference fixtures. As a verification of our alignment methods we also present results from their application in the WFC system alignment.

8844-3, Session 1

Secondary color correction and tolerance sensitivity: how much can you get away with *(Invited Paper)*

John R. Rogers, Synopsys, Inc. (United States)

As many authors have documented, it is possible to correct secondary color without using special glasses, if there are substantial separations between lenses or groups that are chromatically uncorrected. The trick is to use the separations to "induce" secondary color by allowing the rays of different colors to separate from each other before being refracted by the group that follows. This approach works, but the use of separated and uncorrected groups that correct each other raises the question of tolerance sensitivity, because misalignments between the groups causes imperfect correction of the aberrations. It is generally good practice to correct aberrations within groups, rather than allow the groups to "cross-correct" each other. On the other hand, the use of special glass types to control secondary color directly is often either discouraged for cost reasons, or simply not allowed because of thermal shock sensitivity. Moreover, some optical systems (particularly projector applications) require extremely good secondary color correction – often to a small fraction of a pixel. The important question is how much secondary color can be induced before the increased tolerance sensitivity negates the advantage of the color correction. In this paper, we examine the as-designed and as-built performance of several sample systems that rely on separated groups for the correction of secondary color, and compare the performance to that of systems designed without regard to secondary color correction.

8844-4, Session 1

Gravity and extreme magnetism x-ray polarimeter instrument alignment

J. Allen Crane, NASA Goddard Space Flight Ctr. (United States); Mark Cascia, Cascia & Associates (United States); Keith M. Jahoda, Jean H. Swank, NASA Goddard Space Flight Ctr. (United States)

The NASA Gravity and Extreme Magnetism (GEMS) X-ray Polarimeter Instrument had a technically successful PDR but was not confirmed for implementation in 2012 due to budget concerns. The GEMS team is preparing to re-propose this mission, as the scientific objectives remain compelling and are not being addressed by any operating or approved missions. GEMS will allow astronomers to make a sensitive survey of the polarization of black hole, neutron star, and supernova X-ray sources, providing unique information on many astrophysical phenomena. GEMS instrument requires two mirrors to be positioned on a deployable boom 4.5 meters from twin Polarimeters with accuracy and stability such that the target X-Rays are focused in each Polarimeter. This paper will present an overview of the status of the instrument alignment effort and associated challenges. The paper will describe the alignment tools developed to assess alignment viability: Alignment & Pointing Budgets, STOP Analysis, and Monte Carlo Requirement Analysis. These tools steered refinement of the instrument primary interfaces and integration process, and appropriate apportionment of requirements to meet the overall observatory efficiency. The tools drove mirror interface design to limit thermal effects on the mirror focal length, and the addition of flexures to the mirror sunshields to correct a CTE mismatch stability concern. The paper will also discuss the metrology methodology and statistical solutions employed to overcome alignment challenges posed by the deployable boom. The alignment tools and methodologies employed have helped guide development of a viable design, and instrument integration and test process for GEMS.

8844-5, Session 2

Optical alignment of the Global Precipitation Measurements (GPM) star trackers

Samuel E. Hetherington, NASA Goddard Space Flight Ctr. (United States); Dean Osgood, Vicki Roberts, Joseph C. McMann, James E. Gill, Kyle McLean, NASA Goddard Space Flight Ctr. (United States) and QinetiQ North America (United States)

The optical alignment of the star trackers on the Global Precipitation Measurements (GPM) core spacecraft at NASA Goddard Space Flight Center (GSFC) was challenging due to the layout and structural design of the GPM Lower Bus Structure (LBS) in which the star trackers are mounted as well as the presence of the star tracker shades that blocked line-of-sight to the primary star tracker optical references. The initial solution was to negotiate minor changes in the original LBS design

to allow for the installation of a removable item of ground support equipment (GSE) that could be installed whenever measurements of the star tracker optical references were needed. However, this GSE could only be used to measure secondary optical reference cube faces not used by the star tracker vendor to obtain the relationship information and matrix transformations necessary to determine star tracker alignment. Unfortunately, due to unexpectedly large orthogonality errors between the measured adjacent cube faces and the lack of cube calibration data, we required a method that could be used to measure the same reference cube faces as originally measured by the vendor.

We describe an alternative technique to theodolite auto-collimation for measurement of an optical reference mirror pointing direction when normal incidence measurements are not possible. This technique was used to successfully align the GPM star trackers and has been used on a number of other NASA flight projects. We also discuss alignment theory as well as a GSFC developed theodolite data analysis package used to analyze angular metrology data.

8844-7, Session 2

Integration and alignment of ATLAS instrument engineering model components in Optical Development System Lab

Tyler C. Evans, John P. Lehan, SGT, Inc. (United States)

The Optical Development System Lab (ODSL) has matured from testing and aligning prototypes to testing engineering models that are representative of the flight components. Through this process many lessons have been learned that can be directly applied to flight integration and testing, helping drive down risk, cost, and schedule for the overall science instrument. The main ICESat-2 instrument is the Advanced Topographic Laser Altimeter System (ATLAS). It measures ice elevation by transmitting laser pulses, and collecting the reflection in a telescope. Because the round trip time is used to calculate distance, alignment between the outgoing transmitter beam and the incoming receiver beams are critical. An automated closed loop monitoring control system is currently being tested at the engineering model level to prove out implementation for the final spacecraft. To achieve an error of less than 2 micro-radians, an active deformable mirror was used to correct the lab wave front from the collimated “ground reflection” beam. The lab includes a focal plane assembly set up, a one meter diameter collimator optic, a 0.8 meter flight spare telescope for alignment, and the appropriate flight software to control the transmit beam path. By having a fully integrated system with prototypes and engineering units, lessons can be learned before flight designs are finalized.

8844-9, Session 2

High-power laser parabola focus modelling at the Central Laser Facility

Robert I. Heathcote, Robert J. Clarke, Trevor B. Winstone, Peta S. Foster, Science and Technology Facilities Council (United Kingdom)

For many years parabolic mirrors have been used as the primary focusing optics of short pulse high power lasers. Pushing the boundaries of the highest focused intensities requires not only increases in peak laser power but also exploring the limits of focal spot size. Modelling has been performed at the Central Laser Facility to evaluate the performance and tolerance of alignment of a variety of on and off axis parabolic mirrors and their limitations in correcting beam aberrations. Practical considerations such as debris shields and the mounting have also been assessed for their effects on the focal spots. Also modelling as an aid for practical alignment of parabolic mirrors to produce the tightest focal spots is presented.

8844-22, Session 2

Some effects of temperature gradients on the performance of imaging systems and their tolerances

Dmitry Reshidko, José Sasián, College of Optical Sciences, The Univ. of Arizona (United States)

A temperature change has the major effects in an optical system of changing the index of refraction and the geometry of the lens elements according to the coefficient of thermal expansion. These two effects induce first-order imaging changes and aberrations which may degrade performance of the optical system. We discuss the effects from a lens uniform temperature change, a temperature gradient from a uniform heat load across the lens, and a lens edge temperature change. We provide formulas to estimate and tolerance the optical effects from these temperature changes.

8844-11, Session 3

Alignment and testing of a telecentric zoom lens used for the Cygnus x-ray source

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Cygnus is a high-energy radiographic x-ray source. Three large zoom lenses have been assembled to collect images from large scintillators. A large elliptical pellicle (394 x 280 mm) deflects the scintillator light out of the x-ray path into an eleven-element zoom lens coupled to a CCD camera. The zoom lens and CCD must be as close as possible to the scintillator to maximize light collection. A telecentric lens design minimizes image blur from a volume source. To maximize the resolution of objects of different sizes, the scintillator and zoom lens are translated along the x-ray axis, and the zoom lens magnification changes. Zoom magnification is also changed when different-sized recording cameras are used (50 or 62 mm square format). The LYSO scintillator measures 200 x 200 mm and is 5 mm thick. The scintillator produces blue light peaking at 435 nm, so special lens materials are required. By swapping out one doublet and allowing all other lenses to be repositioned, the zoom lens can also use a CsI(Tl) scintillator that produces green light centered at 540 nm. All lenses have an anti-reflective coating for both wavelength bands. Two sets of doublets, the stop, the scintillator, and the CCD camera move during zoom operations. One doublet has x-y compensation. Alignment of the optical elements was accomplished using counter propagating laser beams and monitoring the retro-reflections and steering collections of laser spots. Each zoom lens uses 60 lb of glass inside the 340 lb mechanical structure and can be used in either vertical or horizontal orientation.

8844-12, Session 3

Double Zernike polynomials and its application in optical alignment

Ming-Sen Tsao, Chao-Wen Liang, National Central Univ. (Taiwan)

The Zernike polynomials has been widely used in optical testing and lens design due to its orthogonality, balanced aberration contribution and its connection with the Seidel aberration polynomials. The combination of

one of the Zernike polynomials of pupil coordinate and the other Zernike polynomials of field coordinate is a four dimensional polynomials that can be used to describe the full-field performance of the optical system. This polynomial is said as the double Zernike polynomials (DZP). The full field aberration of an optical system can be fully described by the double Zernike polynomial with the coefficients of each polynomial terms by least squares fitting of the four dimensional wavefront. The aberration behavior of the perturbed or misaligned optical system can also be observed effectively by looking into the difference of the DZP coefficients after the perturbation. In this research paper, we use the Gram-Schmidt orthogonalization process to generate an DZP polynomials that is not only orthogonal over circular pupil but also the rectangular field. The implemented numerical example is a three-mirror anastigmatic telescope with bi-lateral symmetry. Finally, we perturbs the system and evaluate the system with the DZP. The method to align the perturbed optical system with DZP is also discussed.

8844-13, Session 3

FTDT modeling of chip-to-chip waveguide coupling for optical quilt packaging

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We perform Finite-Difference Time-Domain (FTDT) simulations to explore feasibility of chip-to-chip waveguide coupling via Optical Quilt Packaging (OQP). OQP is a newly proposed scheme for wide-bandwidth, highly-efficient waveguide coupling and is suitable for direct optical interconnect between semiconductor optical sources, optical waveguides, and detectors via waveguides. This approach leverages advances in “Quilt Packaging®” (QP), an electronic packaging technique wherein contacts formed along the vertical faces are joined to form electrically-conductive and mechanically-stable chip-to-chip contacts. In OQP, waveguides of separate substrates are aligned with sub-micron accuracy by protruding lithographically-defined copper nodules on the side of a chip. With OQP, high efficiency chip-to-chip optical coupling can be achieved by aligning waveguides of separate chips with sub-micron accuracy and reducing chip-to-chip distance. We used MEEP, a free electromagnetic simulation software package, to investigate the feasibility of OQP by calculating the optical coupling efficiency. Transmission between a typical QCL ridge waveguide and a single-mode Ge-on-Si rib waveguide was calculated to exceed 65% when an interchip gap of 0.5 µm and to be no worse than 20% for a gap of less than 4 ?m. These results compare favorably to conventional off-chip coupling. To further increase the coupling efficiency and reduce sensitivity to alignment, we used a horn-shaped Ge-on-Si waveguide and found a 13% increase in coupling efficiency when the horn is 1.5 times wider than the wavelength and 2 times longer than the wavelength. Also when the horizontal misalignment increases, coupling efficiency of the horn-shaped waveguide decreases at a slower rate than a ridge waveguide.

8844-14, Session 3

Modified point diffraction interferometer to evaluate tolerances in the design of progressive addition lenses

Sara Chamadoira, Univ. de Santiago de Compostela (Spain) and INDO Lens Group (Spain); José Sasián, College of Optical Sciences, The Univ. of Arizona (United States); Eva Acosta, Univ. de Santiago de Compostela (Spain)

The primmary aim of this work is to show the principles, design and performance of a modifed point diffraction interferometer (PDI) to evaluate the local higher order aberrations of progressive addition lenses (PAL’s) in order to anylize the tolerances of the design of these ophthalmic components for a reasonable level of confort in the different users.

The main modification of the PDI is the increment of the size of the “point”, i.e., the size of the pinhole. From the required sizes for high accuracy inerferometry of about fractions of microns, to several microns in this tailored version. The increasement of the size of the pinhole allows an easier alignemnet of the interferometer at expenses of reducing the interference region as well as the accuracy. Nevertheless the first problem represents, in fact, and advantage for our purposes and the accuracy is enough for visual purposes: Aberrations can be measured with an accuracy of lambda/10 with this tailored point diffraction interferometer.

We will also present the analysis of high order aberrations in 6 different PAL’s in circular regions within the 4 most relevant regions of interest (ROI) of the lenses. Each ROI will be studied for radius ranging from 0.4 to 2.4mm. The designed interferometer also allows easily choosing the position and number of the ROI’s by only axial and transversal movements of the semitransparent plate containing the pinhole. The device is compact, robust and accurate, the operational principle is very simple and it provides directly the local high order aberrations without adding an additional part in the interferometer.

8844-15, Session 4

Discrepancies when analyzing and testing high-aperture lenses with pupil aberration

Joseph R. Mulley, Melles Griot (United States)

Lenses with high numerical apertures can be optimized and manufactured to produce diffraction-limited performance across an entire field-of-view while having significant pupil aberration. Understanding the functions of the lens in the application is important when designing, modeling, and testing the lens. Optimization is generally based on RMS wavefront error due to its speed. Most modern optical software correctly takes into account the need for chief-ray aiming but can still model such systems differently from one another, including the reporting of RMS values. These differences can affect the expected nominal performance, both on- and off-axis, and can therefore complicate technical discussion and have an effect on tolerancing. Polychromatic performance can be affected as well. How the lens is tested, for instance with an interferometer, can lead to further discrepancies between the modeled performance, actual system function, and the test data. These differences are explored in the case of a high NA objective lens. The reasons for these differences are examined.

8844-16, Session 4

Highly-accurate measurement of lens surface distances inside of optical assemblies for quality testing

Patrik Langehanenberg, Dennis Off, Bernd Lueerss, TRIOPTICS GmbH (Germany)

In the assembly of multi-component optical systems the precise positioning of every single lens element respectively lens surface is key to reach an optical performance that corresponds to the optical design. Here, in addition to lateral decentering of single elements – such as shift and tilt – the accurate positioning of the optical surfaces along the optical axis is an essential requirement.

In this contribution we present the highly accurate determination of lens center thicknesses and air gaps of optical assemblies in a non-contact manner. The measurement technique is based on time-domain optical coherence tomography. Here, a short coherent interferometer signal is recorded in a Michelson-type setup as a function of a variable optical delay in the reference arm. Whenever the variable optical path length matches the path length to a lens surface, a coherence peak occurs.

Thus, relative surface distances can be derived from the optical delay between two peaks. For a highly-accurate measurement a precise determination of the optical delay length with minimized Abbe-errors is required. Here, a precise long-coherent reference interferometer is superimposed to the short-coherent signal in the optical delay line. Both signals are recorded simultaneously; subsequently, the data is transferred to a PC system for the analysis.

With the presented technique lens thicknesses and air spacings of up to 800 mm can be measured with a resulting accuracy significantly below 1 µm. The obtained results can be used for the compensation of potential deviations/errors in the manufacturing process or for quality control using a pass/fail-evaluation.

8844-17, Session 4

A new approach for the verification of optical systems

Muhammad Umair Siddique, Vincent Aravantinos, Sofiene Tahar, Concordia Univ. (Canada)

Optical systems are increasingly used in microsystems, telecommunication, aerospace and laser industry. Due to the complexity and sensitivity of optical systems, their verification poses many challenges to engineers. Traditionally, the analysis of such systems has been carried out by paper-and-pencil based proofs and numerical computations. However, these techniques cannot provide accurate results due to the risk of human error and inherent approximations of numerical algorithms. In order to overcome these limitations, we propose to use theorem proving (i.e., a computer-based technique that allows to express mathematical expressions and reason about them by taking into account all the details of mathematical reasoning) as an alternative to computational and numerical approaches to improve optical system analysis in a comprehensive framework.

In particular, this paper provides a higher-order logic (a language used to express mathematical theories) formalization of geometrical optics in the HOL Light theorem prover. Based on the multivariate analysis library of HOL Light, we formalize the notion of light ray and optical system (by defining medium interfaces, mirrors, lenses, etc.), i.e., we express these notions mathematically in the software. This allows us to derive general theorems about the behavior of light in such optical systems. In order to demonstrate the practical effectiveness, we verify formally the stability of some resonators: Fabry Perot resonator with fiber rod lens and triangular resonator. The source code developed in this research is available for download and thus can be used by other researchers and engineers for the analysis of their optical systems.

8844-18, Session 4

The importance of optical methods and instruments in structural monitoring

Gheorghe M. Radulescu, Corina E. E. I. Radulescu, Technical Univ. of Cluj Napoca (Romania)

This paper addresses an extremely current field considering the conditions of building, with increasingly ambitious geometrical parameters, such constructions as television towers and smoke towers over 300 meters tall, civil construction over 800 meters tall, bridges over 20 km long, etc.

Structural monitoring is a component of any building's life, but in the case of the structures mentioned it is mandatory and very important in order to know the behavior "in situ" of a certain construction, the monitoring data practically validating the chosen design solution. Optical devices, i.e. theodolites, levels, GPS technologies, fiber optic sensors are essential in this activity. These instruments register how the structure responds to different loads/stress factors and allows the designer to check if the behavior meets the expectations set out in the design solution. The paper is a classification of these instruments and highlights, through examples, the position and importance thereof in SM and the fact that this application of optics is indeed crucial

8844-19, Session PMon

The measurement and alignment for lens group in telescope

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As a frequent part of optical systems, the lens group plays an important role in the large aperture optical system. But the lens group itself is not a good optical system, which could not be test directly after alignment. The paper gives a new method for measurement of the lens group after alignment. Firstly the single element should be measured, and then it is crucial that adds a concave spherical mirror with small aperture as the assistant element. It is not only important for measuring the wavefront of the lens group, but also significant for alignment analysis. The low order aberration such as coma, astigmatism and spherical aberration would be separated from aberration of manufacture. And according to the sensitivity of these aberrations, it is feasible that use the measurement process to iterative the alignment till these aberrations eliminated. About the new method, there are two typical aspects for example. One is that it uses the lens group as null lens for aspheric measurement; the other is that the lens group is used for aberration corrector, such as large telescope optical system. In aspect of aspheric test, the paper gives a measurement process of a concave elliptical mirror. The auto-collimation optical system for measurement includes interferometer, measured mirror and a small lens group that contains 2 spherical lenses. For the second aspect, the paper introduces a telescope with prime focus, which has wide field of view and large relative aperture. The optical system consists of primary mirror and a lens group corrector, the latter contains 4 elements, 3 spherical lenses and 1 elliptical lens. About the measurement after alignment of the two lens group, the paper analyzes the disadvantage during current measurement of the lens group, and then with adding one simple optical element as assistant. The paper measurement the both lens group, and All of the results of measurement are satisfying the requirement of design. The figure errors of spherical lenses are less than 0.1 fringe in the first step, and the figure errors of ellipsoid lens are less than $\lambda/30$ (RMS), the wavefront error at the third step is less than $\lambda/30$ (RMS). Finally, according to the result of measurement, the comparison of analyzed results and test results proves the reliability and precision of this method, which derives that the precision of measurement is better than 0.01λ. At last, directing with the measurement result, the optic quality of lens group after final alignment meet the design requirement.

8844-20, Session PMon

Development of a medium-size SWIR imaging telescope: integration, calibration, and MTF measurement

Ozgur Yilmaz, Ozgur Selimoglu, Fethi Türk, TÜBITAK UZAY (Turkey)

Imaging telescopes comprising of a reflective objective and an electronic detector are popular remote sensing devices for both earth observation and space exploration. Telescope is gathering the light and focuses it on the sensing element, a detector, and detector gives the image on its pixels. Since these devices require high signal to noise ratio, a large mirror at the optical aperture is very common.

Development of an imaging telescope with a large mirror, after the design stage, can be classified into two parts; integration and testing. Integration stage has also two steps; alignment of mirrors and placement of the detector. Testing part includes geometric and radiometric calibrations, and finally MTF measurement. MTF of an imaging system is the final and decisive parameter which shows that everything works well in the system. Currently all these steps are taken in a full-equipped laboratory with expensive devices such as collimators, interferometers and integrating spheres.

In this paper we investigate the methods of development and characterization of an imaging telescope using CMM (Coordinate

Measurement Machine) and scene-based techniques. Alignment of mirrors was realized by CMM . Detector was placed by the help of CMM and an image of a ruled outside building. Radiometric calibration was done with open-sky images. And finally MTF of the system was measured using stellar images. All these techniques do not require any auxiliary device except CMM. Scene-based calibration and MTF measurement can be repeated after the installation of telescope.

We found that MTF of our telescope is greater than %15 all along the detector at 20 lp/mm, which is the Nyquist frequency of 25 μm pixel size. This shows that alignment and focus adjustments work well enough in the telescope. These simple techniques can be used for the development and characterization of a medium-size and medium-resolution imaging telescopes.

8844-21, Session PMon

Optical phase retrieval method for the thermal deformation of space telescope's large primary mirror in the progress of alignment

Fan-jiao Tan, Harbin Institute of Technology (China)

Though it can protect optical system against outside temporary by sealing the major optical path, the primary, as the first collecting aperture, can not be protected by sealing, so which is effected firstly. So it is necessary to analysis the reflecting surface deformation of large primary mirror caused by surface temperature. If the primary mirror is effected by space environment temperature, the surface shape would occurs deformation, consequently the ideal reflecting wave front phase would be changed corresponding. So that the changing phase of practical wave front expresses the deformation variation of primary mirror surface. The papers rebuild the distorted wave front phase distribution by the way of analyzing the reflecting wave intensity. Effected by some temperature grade ,the deformation of large primary mirror surface is worse on the edge. The ideal point source in the entrance pupil is imaged by distorted surface, so the light intensity of the point source varies on the exit pupil. According to the intensity distribution and using least-square method, it can build the phase distribution of deformation wave front on the side of system exit pupil, thus can rebuild the mirror surface deformation by the phase information. From the analysis result, the maximum deformation rebuilding error is 0.033λ. So it can get that by the way of analyzing reflecting wave front optical intensity to get the phase distribution, it can rebuild the mirror deformation caused by surface thermal effect in high precision.

8845-1, Session 1

Ultrafast 3D imaging of isolated molecules with electron diffraction *(Invited Paper)*

Jie Yang, Christopher Hensley, Martin Centurion, Univ. of Nebraska-Lincoln (United States)

Imaging of isolated molecules with atomic resolution has been a longstanding scientific challenge. The majority of the known molecular structures have been determined using x-ray diffraction for crystallized molecules and Nuclear Magnetic Resonance (NMR) spectroscopy for molecules in solution. However, for isolated molecules there has been no method demonstrated to measure the three dimensional structure. Electron diffraction has been the main tool to determine the structure of molecules in the gas phase. In this method the diffraction pattern is compared with a calculated structure iteratively until a good match between experiment and theory is found. Diffraction patterns from randomly oriented molecules in the gas phase contain only one-dimensional information, and thus input from theoretical models is needed to recover the structure. We show that a three-dimensional image of a molecule can be reconstructed from electron diffraction patterns of laser-aligned molecules without any prior knowledge of the structure. The molecules are impulsively aligned with a femtosecond laser pulse and probed with femtosecond electron pulses in a field-free environment at the peak alignment. In this talk, I will show first results on simple molecules and how to generalize the method to more complex molecules. In addition, our setup can be used to investigate dynamics on ultrafast time scales with newly available femtosecond electron sources.

8845-2, Session 1

Ultrafast dynamic imaging of molecules with laser induced electron diffraction method *(Invited Paper)*

Chii-Dong Lin, Kansas State Univ. (United States); Junliang Xu, Lou DiMauro, Pierre Agostini, Cosmin Blaga, The Ohio State Univ. (United States)

When a molecule is placed in an intense few-cycle mid-infrared laser pulse, an electron which was released earlier in the pulse may be driven back by the laser field to recollide with the parent molecular ion. These returning electrons are analogous to a beam of laboratory prepared electrons used in the traditional electron diffraction experiment for probing the structure of molecules, but with the advantage that its pulse duration is of the order of a few femtoseconds. Based on theoretical analysis, we established that if the returning electrons have energies of the order of 100 eV or more, and if the electrons are backscattered by the target, then the resulting diffraction images can be analyzed using the same theory used in conventional electron diffraction method where electron beams have energies in the order of hundreds of keV's, but the scattering images are taken at forward angles. The advantage of laser induced electron diffraction method is that we can use few-femtosecond laser pulses that are already available. From the diffraction images generated by oxygen molecules using mid-infrared lasers, we showed that the bond length change of 0.1 Angstrom in five femtoseconds can be retrieved, thus for the first time establishing dynamic imaging with few femtosecond temporal resolution and sub-Angstrom spatial resolution.

8845-3, Session 1

Use of attosecond electron pulses to image electronic motion in atoms and molecules *(Invited Paper)*

Anthony F. Starace, Hua-Chieh Shao, Univ. of Nebraska-Lincoln (United States)

Ultrafast electron diffraction and microscopy have advanced significantly, enabling observation of transient structures in chemical reactions. The temporal widths of these electron pulses, however, range from fs to ps, which is inadequate for studying typical electronic motions in atoms and molecules. Recently, methods have been proposed for producing single-electron, attosecond pulses. The attosecond (as) temporal and sub-Å spatial resolutions of such ultrashort high energy electron pulses would enable four-dimensional (4D) study of electronic motion. We present here theoretical simulations demonstrating the potential of such attosecond electron pulses for 4D imaging of electronic motion in two prototypical systems: the H atom and the H2+ molecule. For the H atom, a few-fs laser pulse is proposed to excite a coherent superposition of two electronic states (the 3p and 4p levels of the H atom); for the H2+ molecule we consider a coherent superposition of two molecular states (the ?g1s and the ?u1s states). In both cases the charge distribution oscillates with the beat frequency of the coherently superposed states. For a 110 as electron pulse with energy of 10 keV we have investigated elastic differential scattering from these oscillating electronic states of H and H2+ [1] and inelastic scattering from the H atom target. Recently, we have also investigated ultrafast electron impact ionization (e,2e) processes for both the H and H2+ targets, which enable one to directly image the time-varying momentum distribution of the target electronic states.

Reference:

[1] H.-C. Shao and A.F. Starace, Phys. Rev. Lett. 105, 263201 (2010).

8845-4, Session 1

Ultrabright low-repetition rate femtosecond electron sources: perspectives and challenges towards the study of structural dynamics in biological systems *(Invited Paper)*

Germán Sciaini, Univ. Hamburg (Germany)

One of the great dream experiments in Science is to directly observe atomic motions as they occur in chemical reactions and phase transformations. Femtosecond electron diffraction provided the first “light” of sufficient intensity to achieve this goal by attaining atomic resolution to structural changes on the relevant timescales. During my talk I will cover the technical progress that made this new level of acuity possible and give a survey of the new insights gained from an atomic level perspective of structural dynamics. Atomic level views of various structural processes are going to be discussed in light of the degree of directional bonding in the material - . Concepts such as non-thermal melting1,3 and ultrafast structural order parameters in low-dimensional systems are directly observable at the atomic level of inspection. For the delight of chemists, I will finalize my talk showing very recent results obtained for a labile organic crystal composed by light scattering centers. Here, we implemented a recently developed ultra-bright femtosecond electron source to obtain an atomically-resolved movie of the relevant molecular motions driving the photo-induced insulator-to-metal phase transition in the organic charge-transfer salt (EDO-TTF)2PF6. This study is the first in its kind and illustrates the potential of femtosecond electron sources to provide new insights into more complex structural phenomena relevant to chemistry and biology.

8845-5, Session 1

Photon-induced near field electron microscopy *(Invited Paper)*

Sang Tae Park, Ahmed H. Zewail, California Institute of Technology (United States)

Ultrafast electron microscopy in space and time domain utilizes a pulsed electron probe pulse to directly map structural dynamics of nanomaterial initiated by an optical pump pulse, in imaging, diffraction, spectroscopy, and their combinations. It has demonstrated its capability in the studies of phase transition, mechanical vibration, and chemical reaction. Moreover, electrons can directly interact with photons via near field component of light scattering by nanostructure, and either gain or lose light quanta discretely in energy. By energetically selecting those electrons that exchanged photon energies, we can map this photon-electron interaction, and is termed photon-induced near field electron microscopy (PINEM). Here, we give an account of the experimental observations and the theoretical understanding of PINEM. Experimentally, nanostructures such as sphere, cylinder, disk, and triangle have been investigated. Theoretically, time-dependent Schrödinger and Dirac equations for an electron under light are directly solved to obtain analytical solutions. The interaction probability is expressed by a mechanical work done to an electron by optical wave, which can be evaluated analytically by the near field components of the Rayleigh scattering for small spheres and thin cylinders, and numerically by the discrete dipole approximation for other geometries. Understanding of the phenomenon allows us to realize its potential applications.

8845-6, Session 1

Diffraction contrast as a sensitive indicator of femtosecond motion in ultrafast transmission electron microscopy

David J. Flannigan, Univ. of Minnesota (United States)

With ultrafast transmission electron microscopy (UTEM), access can be gained to the spatiotemporal scales required to directly visualize rapid, non-equilibrium structural dynamics of materials. This is achieved by operating a transmission electron microscope (TEM) in a stroboscopic pump-probe fashion by photoelectrically generating coherent, well-timed electron packets. These probe photoelectrons are accelerated down the TEM column where they travel through the specimen before reaching a standard CCD detector. A second laser pulse is used to excite (pump) the specimen in situ. Structural changes are visualized by varying the arrival time of the pump laser pulse relative to the probe electron packet at the specimen. Here, I will discuss how ultrafast nanoscale motions of crystalline materials can be visualized and precisely quantified using diffraction contrast imaging in UTEM. Because diffraction contrast sensitively depends upon both crystal lattice orientation as well as incoming electron wavevector, minor spatial/directional variations in either will produce dynamic and often complex patterns in real-space images. This is because sections of the crystalline material that satisfy the Laue conditions may be heterogeneously distributed such that electron scattering vectors vary over nanoscale regions. Thus, minor changes in either crystal grain orientation, as occurs during specimen tilting, warping, or anisotropic expansion, or in the electron wavevector result in dramatic changes in the observed diffraction contrast. In this way, dynamic contrast patterns observed in UTEM images can be used as highly sensitive indicators of ultrafast specimen motion. Further, these motions can be spatiotemporally mapped such that direction and amplitude can be determined.

8845-7, Session 2

Sum-frequency-generation (SFG) vibration spectroscopy study of crystalline cellulose in biomass *(Invited Paper)*

Seong H. Kim, The Pennsylvania State Univ. (United States)

The crystallographic information of the unit cell for the purified cellulose I-alpha and I-beta crystals provided foundations for understanding molecular interactions and packing between cellulose chains. However, little is known about how crystalline cellulose is assembled in intact plant cell walls, bacterial pellicles, and animal tissues. This question could be addressed by sum-frequency-generation (SFG) vibration spectroscopy [A. L. Barnette, et al. Biomacromolecules2011, 12, 2434-2439], which can selectively detect hierarchical ordering of crystalline cellulose in biomass without spectral interference from non-cellulosic components. This talk will address the structural interpretation and quantitative analysis of SFG signals from crystalline cellulose in various cellulose-producing organisms that have not been treated for isolation of cellulose. The SFG spectra of cellulose samples from different species revealed drastic differences in the relative distribution of SFG peaks, which cannot be explained with the structural information obtained from the x-ray diffraction (XRD) and infrared (IR) analyses of the same samples.

8845-8, Session 2

Probing ferroelectrics using optical second harmonic generation microscopy *(Invited Paper)*

Venkatraman Gopalan, The Pennsylvania State Univ. (United States)

Nonlinear Optics is emerging as a powerful imaging modality in materials science as well as life sciences. In this talk, I will present probing polar materials using confocal second harmonic generation microscopy (SHG). New ferroelectric phases with enhanced properties are discovered in classic ferroelectrics such as BaTiO3 and KNbO3 that were discovered over 60 years ago. New polar phenomena are discovered even in nominally nonpolar materials such as CaTiO3. Theoretical modeling of the SHG polarimetry results provide information about the point group symmetry and orientation of the polar domains.

8845-9, Session 2

Studies of hydrophobic organic molecules at water interfaces using phase-sensitive sum frequency vibrational spectroscopy *(Invited Paper)*

Chuanshan Tian, Fudan Univ. (China)

Hydrophobic organic molecules, because of the nature of their “hydrophobicity”, at a water interface had been supposed to have a little effect on water structure. Surprisingly, strong ion adsorption, such as OH-, Cl-, was found at (hydrocarbon) hydrophobic molecule/water interface, which sets up a surface field near the interface thus causing drastic reorientation of water molecules near the interface [1]. We have used phase-sensitive sum frequency vibrational spectroscopy (PS-SFVS) to probe the effects of solvated ions on the structure of hydrophobic molecules/water interfacial systems, including octadecyltrichlorosilane (OTS), Hexane, polyethylene, etc. In probing the interfacial water structure with SFVS, care was taken to make sure that the bulk contribution of water is negligible. Significant interactions between hydrophobic chains and hydroxyl ions are revealed. By varying the ion concentration in the bulk water, the adsorption isotherm was measured. The result shows that even the neat water/hydrophobic molecules interface is not neutral, but charged with hydroxyl ions (OH-). The possible mechanism of ion adsorption at the hydrophobic interfaces will be discussed.

References:

[1] C.S. Tian, and Y. R. Shen, Proc. Natl. Acad. Sci. USA 106?15148(2009)

8845-11, Session 3

Nanophotonics for information processing *(Invited Paper)*

Yeshaiahu Fainman, Univ. of California, San Diego (United States)

Various future system applications that involve photonic technology rely on our ability to integrate it on a chip to augment and/or interact with other signals (e.g., electrical, chemical, biomedical, etc.). For example, future computing and communication systems will need integration of photonic circuits with electronics and thus require miniaturization of photonic materials, devices and subsystems. Another example, involves integration of microfluidics with nanophotonics, where former is used for particle manipulation, preparation and delivery, and the latter in a large size array form parallel detection of numerous biomedical reactions useful for healthcare applications. To advance the nanophotonics technology we established design, fabrication and testing tools. The design tools need to incorporate not only the electromagnetic equations, but also the material and quantum physics equations to include near field interactions. These designs are integrated with device fabrication and characterization to validate the device concepts and optimize their performance. Our research work emphasizes the construction of passive (e.g., engineered composite metamaterials, filters, etc.) and active (e.g., nanolasers) components on-chip, with the same lithographic tools as electronics. In this talk, we discuss some of the passive metamaterials and devices that recently have been demonstrated in our lab. These include our most recent results on monolithically integrated short pulse compressor utilized with SOI material platform and design, fabrication and testing of nanolasers constructed using metal-dielectric-semiconductor resonators confined in all three dimensions.

8845-12, Session 3

STED optical nanoscopy with organic and inorganic dyes *(Invited Paper)*

Peng Xi, Peking Univ. (China)

The conventional microscopy can only yield optical resolution approaching Abbe diffraction limit of ~200 nm. This is still larger than many subcellular structures, which are too small to be resolved in detail. These limitations have driven the development of super-resolution optical imaging methodologies over the past decade.

In stimulated emission depletion (STED) microscopy, the excitation focus is overlapped by an intense doughnut-shaped spot to instantly de-excite markers from their fluorescent state to the ground state by stimulated emission process. This effectively eliminates the periphery of the fluorescent Point Spread Function (PSF), resulting in a narrower focal region, or super-resolution. Yet, since the organic dye is prone to the ON-OFF process of STED, they suffer from photobleaching severely in STED nanoscopy. One alternative is to seek the approach of inorganic dye.

In this work, we present the application of STED nanoscopy in subcellular organelle imaging. With two excitation lasers of 532 nm and 635 nm, and the depletion laser of 760 nm, dual-color STED has been used in the study of colocalization of human respiratory syncytial virus. Fluorescent nano-diamond has been imaged as a photostable inorganic dye. With novel upconversion nanoparticles as fluorescent labels, we have achieved super-resolution with power levels 2 orders of magnitude than conventional STED nanoscopy with organic dyes.

8845-13, Session 3

Self-assembled nano-materials for nonlinear fiber optics and tunable plasmonics *(Invited Paper)*

Yong Xu, Islam Ashry, Ishac Kandas, Hans D. Robinson, James R. Heflin, Virginia Polytechnic Institute and State Univ. (United States)

Since silica is an amorphous material with full inversion symmetry, silica-based microstructures cannot possess significant second-order nonlinearity. We recently developed a method that can potentially overcome this deficiency by coating a silica fiber taper with layers of radially aligned nonlinear molecules. The coating process can be accomplished through layer-by-layer self-assembly, where the alignment of the nonlinear molecules is maintained through electrostatic interaction. As a result, the nonlinear fiber structures are thermodynamically stable and can generate significant second-order nonlinear responses despite their full rotational symmetry. This prediction has been experimentally confirmed through SHG measurements. To further enhance the overall second order nonlinearity, we have developed a laser ablation based approach that can generate second-order nonlinearity that is spatially periodic along the fiber taper. Our preliminary experiments suggest that SHG intensity can be enhanced by such quasi-phase matching configurations.

A similar approach has been developed for constructing tunable plasmonic systems. As a proof-of-concept study, we assembled swellable polymer films over a planar Au substrate through layer-by-layer assembly and covered the swellable polymer with a monolayer of quantum dots. After immersing the swellable plasmonic structure in solution and adjusting its pH value, we used an atomic force microscope and fluorescence lifetime measurements to demonstrate that the thickness of the swellable polymers can be modified by as much as 300%. Through fluorescence lifetime studies, we also confirmed that the plasmonic resonance can be significantly changed by the swellable polymers.

8845-14, Session 3

Study of electronic properties of epitaxial graphene using coherent controlled photocurrent injection *(Invited Paper)*

Dong Sun, Peking Univ. (China)

In this talk, we report generation of ballistic electric currents in unbiased epitaxial graphene at 300 K via quantum interference between phase-controlled cross-polarized fundamental and second harmonic 220 fs pulses. The transient currents are detected via the emitted terahertz radiation. Based on this coherent controlled photocurrent injection method, we have studied various electronic properties of epitaxial graphene.

In one experiment, we have measured the third-order nonlinear tensor in epitaxial graphene as a novel approach to probe interlayer electronic coupling, by studying THz emission from coherently controlled photocurrents as a function of the optical pump and THz beam polarizations. We find that the polarization dependence of the coherently controlled THz emission expected from perfectly uncoupled layers, i.e. a single graphene sheet, is not observed. A model calculation, treating the interlayer coupling as bilayer coupling with variable strength, qualitatively reproduces the polarization angular dependence, providing evidence for coupling.

In another experiment, we use coherent control with ultrashort optical pulses to photoinject a current and detect the terahertz (THz) radiation emitted by the resulting current surge. We pre-inject a background of hot carriers using a separate pump pulse, with a variable delay between the pump and current-injection pulses. We find the effect of the hot carrier background is to reduce the current and hence the emitted THz radiation. The current damping is determined simply by the density (or temperature) of the thermal carriers. The results indicate that hot carriers are effective in damping the current, and are expected to be important for understanding the operation of high-speed graphene electronic devices.

8845-15, Session 4

Correction of blurred image by exploiting phase conjugation based on single second-order nonlinear parametric processes *(Invited Paper)*

Yujie J. Ding, Lehigh Univ. (United States)

During this presentation, we will summary our recent progress made by my group on correction of blurred images caused by atmospheric turbulence by using phase-conjugated beams generated by difference-frequency generation in stacked KTP plates. We have demonstrated that when the incoming beam is phase-distorted the phase-conjugated beam can be used to clean up the distortion. We have further demonstrated that image quality can be restored after the phase distortion. This represents a novel approach for image restoration based on nonlinear optics. The image correction is insensitive to the polarization of the incoming beam. Our approach is instantaneous. Furthermore, the pump power as low as 1 mW is required to reach the nonlinear power reflection coefficient of 100%. Therefore, it is ideal for us to correct the blurred images caused by atmospheric turbulence using our approach.

8845-16, Session 4

Wave mixing of intense terahertz fields and optical pulses in solids: parametric interactions, nonlinear terahertz imaging, and 3D-mapping *(Invited Paper)*

Matteo Clerici, Institut National de la Recherche Scientifique (Canada) and Heriot-Watt Univ. (United Kingdom); Daniele Faccio, Heriot-Watt Univ. (United Kingdom); Lucia Caspani, Institut National de la Recherche Scientifique (Canada); Eleonora Rubino, Univ. degli Studi dell'Insubria (Italy); Marco Peccianti, Istituto dei Sistemi Complessi (Italy); Luca Razzari, Tsuneyuki Ozaki, Roberto Morandotti, Institut National de la Recherche Scientifique (Canada)

Developing novel and high-sensitivity techniques for imaging of terahertz (THz) fields is essential for the increasingly diffused diagnostic applications of such a long wavelength radiation. Although recent technological progresses resulted in more accessible and performing THz space-resolved detectors, there is still a large gap with the silicon-based detectors employed for measuring visible light in terms e.g. of signal-to-noise ratio and costs.

We theoretically and experimentally investigated the four-wave mixing of broadband THz pulses –generated by laser-induced plasma with peak electric fields in the order of few MV/cm and 90 fs duration (full-width at half maximum)– with optical pulses at ? 790 nm carrier wavelength, delivered by a Ti:Sapphire laser, as a mean for THz detection and imaging. For our investigations we employed a diamond crystal as a nonlinear medium, chosen due to its large transmission bandwidth, covering both the UV-VIS as well as the Far-Infrared and THz range.

We show that two parametric processes occur, namely sum- and difference-frequency generation, and that such processes are up-frequency shifting mechanisms able to map the spatial properties of a THz beam into the visible spectrum. Hence, THz beam profiling and imaging can be readily performed by means of a simple (and economic) CCD camera. Furthermore, we show that, among the possible interaction geometries, phase matching is achieved for THz pulses counter propagating with the optical probe beams, which results in a novel and intriguing THz detection scheme. Finally, we will show how full three-dimensional mapping of unknown THz pulses can be performed.

8845-17, Session 4

Applications of swept-fiber-laser-based nonlinear (CARS, SRS) or linear (mid-infrared) molecular spectroscopy system *(Invited Paper)*

Alain Villeneuve Jr., Youngjae Kim, Alexandre Dupuis, Rajeev Yadav, André Archambault, Guido Pena, Mathieu Giguère, Bryan Burgoyne, Joseph Salhany, Genia Photonics Inc. (Canada)

Genia has developed a swept-laser-based nonlinear spectroscopy system using robust and agile all-fiber-based synchronized programmable laser (SL). The system includes a rapidly tunable Ytterbium-Doped-Fiber-based picosecond Programmable laser (PL) suitable for imaging techniques such as Optical Coherence Tomography (OCT) and Second Harmonic Generation (SHG) and a fixed wavelength Master-Oscillator Power Amplifier (MOPA). The MOPA is a fixed wavelength frequency doubled Erbium-Doped-Fiber-based Master-Oscillator Power Amplifier operating at 767.5 nm and/or 792.5 nm. The PL can be wavelength-tuned within the 1020-1080 nm at speed suitable for real time OCT and for Coherent Anti-Stokes Raman Scattering (CARS) and Stimulated Raman Scattering (SRS) spectroscopy in the high wavenumber region (2800-3350 cm-1). Another PL tunable around 850 nm is also under development to address the fingerprint region (800-1660 cm-1). The lasers for the mid-IR linear spectroscopy system mix either 1020-1080 nm, 1530-1605 or 1900-2030 nm to achieve those regions.

The pulse width can be optimized for the long coherence length required for OCT or compressed to a few ps for nonlinear imaging such as SHG. The pulse for CARS/SRS are maintain at 20 ps for the nonlinear spectroscopy to avoid any issues with timing jitter between the two lasers. The difference in energy and the synchronization can be maintained at more than 50 000 wavelengths per second allowing for spectrum to be acquired in about 1 ms.

The system also includes two detectors, a data acquisition card and a computer to control the laser and to display the acquired spectrum. The applications of the system to linear, in the mid-IR, and nonlinear, in the near infrared, molecular spectroscopy will be shown.

8845-18, Session 4

Spectrography for 3D analysis from a single spectral view *(Invited Paper)*

Yan Xi, Jun Zhao, Shanghai Jiao Tong Univ. (China); Xiaojing Huang, Brookhaven National Lab. (United States); Hengyong Yu, Wake Forest Univ. School of Medicine (United States); Yuxin Wang, Argonne National Lab. (United States); Ge Wang, Rensselaer Polytechnic Institute (United States)

Coherent diffraction imaging (CDI) is a lens-less imaging technique for studying non-crystalline samples. Without the limitations of optical elements in lens-based imaging systems, spatial resolution of CDI can be of nanometer-scale. With the great power of x-ray free electron laser (FEL), femtosecond-scale temporal resolution can be achieved, which is critical for uncovering bio-molecular interactions and other processes. However, the huge radiation dose of FEL will destroy a sample with a single exposure, which makes it difficult to perform conventional 3D imaging which demands measurements around the sample. To have 3D analysis from only one view, we proposed a spectral imaging scheme, referred to spectrography. Instead of determining the complete 3D structure of the sample, an initial goal of spectrography is to retrieve those projections of the sample that are not much different from the x-ray propagation direction. In this paper, we extend the spectrography method to image complex samples. Utilizing a weighted difference map algorithm, specific Fourier planes are estimated through the origin of the 3D Fourier space and the measured Ewald sphere. Then, complex x-ray wave fields are reconstructed at different viewing angles. The computed projections provide critical clues on features of interest inside the sample. To demonstrate our proposed method, both numerical and physical experiments were performed. The results suggest that spectrography is practical and effective for 3D analysis of an object from a single spectral view.

8845-19, Session 4

CMOS: compressive multi-heterodyne optical spectroscopy

Nikhil Mehta, The Pennsylvania State Univ. (United States); Jingbiao Chen, Zhigang Zhang, Peking Univ. (China); Zhiwen Liu, The Pennsylvania State Univ. (United States)

High resolution optical spectroscopy facilitates research in fundamental sciences such as analysis of energy levels in atomic and molecular structures, Doppler shift measurements, evaluation and monitoring of fundamental constants; and enables applications such as molecular fingerprinting of gas molecules and identification of drugs and biological species. Recent advances in generation and control of octave spanning laser frequency combs have opened new opportunities for ultra-high resolution optical spectroscopy employing multi-heterodyne scheme. Existing multi-heterodyne techniques based on combining a pair of frequency combs which have slightly different mode spacing yield a discrete spectrum sampled at the comb modes and hence utilize 'dense' combs for improving the frequency sampling. In order to provide continuous frequency coverage across the entire multi-THz optical band without increasing the acquisition time, we propose a general formulation for compressive multi-heterodyne spectroscopy using dynamically encoded frequency comb to map multiplexed optical spectrum to the RF domain. We present proof-of-concept numerical simulations using iterative algorithms based on compressive sensing to take advantage of sparsity inherent in typical optical spectra of interest to reduce the number of RF measurements. We demonstrate the retrieval of a hypothetical 20THz wide optical spectrum using a hypothetical frequency comb with 50GHz mode spacing by using fewer than 25% RF measurements as compared to the number of comb modes. Our results are consistent with the theoretically expected reduction in the number of measurements for successful retrieval based on sparsity-constrained inversion. Our technique applies equally well for both incoherent and coherent (both amplitude and phase) spectrum measurement.

8845-20, Session 5

Using single molecule-imaging method to resolve functional stoichiometry of ion channel *(Invited Paper)*

Liangyi Chen, Peking Univ. (China)

Two proteins, STIM1 in the endoplasmic reticulum and Orai1 in the plasma membrane are required for the activation of calcium release-activated calcium (CRAC) channels at the cell surface. How these proteins interact to assemble functional CRAC channels has remained uncertain. Here we determine how many Orai1 and STIM1 molecules are required to form a functional CRAC channel. We engineered several genetically expressed fluorescent Orai1 tandem multimers and a fluorescent, constitutively active STIM1 mutant. The tandem multimers assembled into CRAC channels as seen by rectifying inward currents and by cytoplasmic calcium elevations. CRAC channels were visualized as fluorescent puncta in total internal reflection microscopy. With single-molecule imaging techniques, it was possible to observe photo-bleaching of individual fluorophores and to count the steps of bleaching as a measure of the stoichiometry of each CRAC channel complex. We conclude that the subunit stoichiometry in an active CRAC channel is four Orai1 molecules and two STIM1 molecules. Fluorescence resonance energy transfer experiments also showed that four Orai1 subunits form the assembled channel. From the fluorescence intensity of single fluorophores, we could estimate that our transfected HEK293 cells had almost 400,000 CRAC channels and that when intracellular Ca^{2+} stores were depleted, the channels clustered in aggregates containing about 1,300 channels, amplifying the local Ca^{2+} entry.

8845-21, Session 5

Biological dynamics and mechanisms studied by ultrafast spectroscopy *(Invited Paper)*

Dongping Zhong, The Ohio State Univ. (United States)

Biological function is a complex process and the understanding of its molecular mechanism is essential for practical applications such as in drug design and gene therapy. Here, we present our recent studies of an important biological system, repair of sun-damaged DNA by photoenzyme photolyase to prevent the potential skin cancer. With femtosecond spectroscopy and molecular biology methods, we have mapped out the entire evolution of repair by following the dynamics from the reactants, to intermediates to final products with a series of elementary reactions including ultrafast cyclic electron transfer and chemical bond breaking and making. These biological dynamics occur ultrafast on the picosecond time scales and are in synergy to maximize repair quantum efficiency. The results are significant and reveal the molecular mechanism and repair photocycle at local atomic scale and provide the molecualr basis for the future medical application.

8845-22, Session 5

Bond-selective imaging: a new window into the unseen world *(Invited Paper)*

Ji-Xin Cheng, Purdue Univ. (United States)

Label-free spectroscopic imaging using inherent chemical bond vibration signals as contrast opens a new window for watching biomolecules and nanomaterials inside living cells and human body. I will present our most recent advances in both development and applications of spectroscopic imaging platforms, including deep tissue imaging by listening to harmonic molecular vibration, study of lipid metabolism in cancer by coherent Raman microscopy, and super-resolution imaging of nanomaterials by transient absorption microscopy. Potentially transformative impacts of these projects will be illustrated.

8845-23, Session 5

Ultrafast optical imaging of microfluidic-scale physiology: opportunities and challenges *(Invited Paper)*

Michael A. Choma M.D., Yale School of Medicine (United States)

Many pediatric diseases are poorly understood, in part because they involve processes that occur at small, microscopic scales. In addition, the causes often involve small motions and fluid flows. For example, an early embryonic heart has a diameter of about 100 micrometers, which is about the diameter of a human hair. The cilia that move mucus out of our airways are even smaller- about 10 micrometers long. In order to better study pediatric disease at such small scales, we develop innovative optical imaging methods to visualize and quantify disease at these microscopic scales. I will discuss (a) the relevant temporal and spatial resolution requirements needed to quantify microfluidic-scale physiology, (b) our ongoing work at the interface of biomedical optics and microfluidic-scale physiology, and (c) the potential clinical impact of ultrafast imaging in microfluidic-scale physiology.

8845-24, Session 5

Highly quantitative label-free three-dimensional single cell imaging *(Invited Paper)*

YanYi Huang, Peking Univ. (China)

We present an optofluidic platform to perform the highly quantitative label-free measurement of single cells using stimulated Raman scattering (SRS) microscopy. Through integration with a microfluidic device that consists of an array of parallel culture chambers, we accurately control the microenvironment of every single cell and observe the cell's response to the environmental changes. SRS microscopy provides a label-free modality to observe the dynamical changes at the sub-cellular level, with the intrinsic three-dimensional sectioning ability. We use this system to monitor lipid metabolism and digitize the lipid droplet distributions and morphology, showing the great potential to study the details of lipogenesis and lipid-associate biological processes.

8845-25, Session 5

On chip optofluidic spectroscopy for biomedical applications *(Invited Paper)*

Zhenyu Li, The George Washington Univ. (United States)

Optical spectrometers have been widely used in biomedical applications such as DNA/RNA quantification, immunoassays and spectral imaging. Recent research on lab-on-a-chip systems has generated considerable interests in miniaturizing optical spectrometers/spectrographs integrated with microfluidic functions. However traditional microfabrication methods and solid state materials present significent challenges in fabricating microfluidics-compatible spectrometer systems. In this paper, I will discuss our efforts of implenting on-chip spectrographs using liquid metallic optofluidic components such as gratings, mirrors and pinholes.

8845-26, Session 5

Raman spectroscopy and optical coherence tomography for skin cancer study

Ivan A. Bratchenko, Valeriy P. Zakharov, Oleg O. Myakinin, Dmitry V. Kornilin, Dmitry N. Artemyev, Samara State Aerospace Univ. (Russian Federation); Alexander A. Moryatov, Sergey V. Kozlov, Samara Regional Clinical Oncological Dispensary (Russian Federation)

Nowadays medical staff notes an increase number of different skin lesions appearing including benign and cancerous tumors. Optimal approach of these disease treatments requires precise determination of invasion borders in healthy skin and noninvasive disease specificity estimation. This requirement may be satisfied by using optical techniques. In this study we demonstrate joint usage of optical coherence tomography (OCT) and Raman spectroscopy (RS) for in vivo and ex vivo skin tumors diagnosis. OCT setup was performed on the basis of a broadband superluminescent laser diode (840 ± 25nm) at the source end, Michelson interferometer with 50/50 split ratio to the sample and reference arms, spectrometer with diffraction grating (1200 gr/mm) and CCD line scan camera (2048 pix, 29.3 kHz) at the detection end. OCT system allowed real-time obtaining of healthy skin and pathologies 3D images. Herewith OCT image resolution was 6 - 8 micrometers that let one accurately determine the invasion area and respectively a resection zone. RS system contained Shamrock sr-303i spectrometer with DV420A-OE digital camera, RPB785 RS probe and LuxxMaster Raman Boxx laser (785nm, 200 - 300 mW). Raman spectrums from different tissues: melanoma, basal call carcinoma, pigment nevi, keratosis, normal skin, were used to identify the main chemical components of formations. Subsequent allocation of formations characteristics based on the Raman peaks intensities was performed. It was found that different skin formations have unique composition of intensities related to the lipid-specific and amide I proteins bands peaks near 1270, 1310, 1459 and 1657 cm-1. Analysis of peaks features observed in the Raman spectrum resulted in the identification criteria for specificity determination of tumors in the healthy skin.

8845-27, Session 6

Early excitation dynamics in conjugated polymers studied by two-dimensional Fourier transform spectroscopy *(Invited Paper)*

Kenan Gundogdu, Cong Mai, North Carolina State Univ. (United States)

Conjugated polymers and their hybrids with fullerenes have tremendous potential for use in low-cost, flexible, light weight opto-electronic applications and can be synthesized and processed to exhibit a variety of electronic behavior from metal-like to insulator. Characterization of primary excitations and their dynamics in pi-conjugated polymers has been an active research area for the last two decades. Yet many controversial views persist regarding the nature of initial optical excitations, as there are gaps in understanding of critical fundamental aspects of their transport, relaxation, and charge separation kinetics. As a result, applications and use of semi-conducting polymers are progressing largely by heuristic approaches. In this work, by using novel two-dimensional Fourier transform spectroscopy (2D FTS) , we provide new fundamental insight on optical processes in polymer. In contrast to the commonly accepted exciton picture, we observed that initially excited electrons and holes exhibit uncorrelated dynamics. While the electrons are static in a rigid environment, the holes are highly diffusive. These results suggest, we have to reconsider common views regarding the early dynamics in polymers.

8845-28, Session 6

Polarization study of all-optical magnetic recording in ferrimagnets

Ivaylo Ivanov, Xiangping Li, Philip Dolan, Swinburne Univ. of Technology (Australia); Yongbing Xu, Jing Wu, The Univ. of York (United Kingdom); Min Gu, Swinburne Univ. of Technology (Australia)

Owing to the ultrafast switching, opto-magnetic recording by a femtosecond pulsed laser beam is of great importance for the next generation of data storage. The tightly focused laser pulse allows data recording to be confined to a diffraction-limited region, offering tremendous potential for high density data storage. It has been demonstrated that circularly polarized light can act as an effective magnetic field through the inverse Faraday effect allowing optical writing of magnetic memory. Recently, it was found that the laser heating itself can also introduce the magnetization reversal, without any dependence on the polarization of the laser beam. The full nature of the dependence of opto-magnetic recording on the polarization of the writing beam is yet to be determined, but is necessary to completely understand the switching mechanism. In this paper, we present a systematic study of optically induced magnetization reversal in TbFeCo films by different polarization states of the femtosecond pulses. The experiments were conducted with single femtosecond pulses at a wavelength of 800 nm. The laser beam was focused with an objective onto a TbFeCo film with a thickness of 20 nm. Magnetization reversal was detected on a charge coupled device with a home-built polarizing microscope. In addition, a theoretical model considering electron heating by the laser pulse, followed by a thermal exchange between electrons and lattice has been developed. The obtained experimental dependencies were explained taking into account this effect and the role of the laser polarization in the heat transfer and magnetization reversal. Two power ranges corresponding to the inverse Faraday effect and laser-heating induced magnetic reversal, respectively, were identified.

8845-29, Session 6

Stable time-domain spectroscopy of femtosecond thermal-infrared pulses using a carrier-envelope-phase locked system

Sheng Liu, Thomas S. Mahony, Daniel A. Bender, Michael B. Sinclair, Igal Brener, Sandia National Labs. (United States)

We build a novel thermal-IR time domain spectroscopy system based on a triple-output near-infrared ultrafast fiber laser, phase-l ocked difference frequency generation (DFG) and phase-matched electro-optic sampling (EOS) that can be used to obtain the full complex electric field of tunable IR pulses. Thermal IR pulses are generated by difference frequency mixing of two pulse trains in a GaSe crystal. Due to the nature of DFG, an unstable carrier to envelope phase (CEP) can occur when the optical path difference between the two generating pulses drifts. To overcome this instability, we phase-lock the CEP of the IR pulse by using near-IR light reflected off the generation GaSe with a piezo controlled delay feedback loop. We fully studied the dependence of the amplitude and shape of the detected IR waveforms on the thickness of GaSe crystals used in DFG and EOS. This is done by varying the phase matching angles of the EOS crystal while fixing the DFG crystal which emits IR pulses centered at ?~9.6 µm. We observe optimum (shape and amplitude) electric field transient when a 500 µm and a 250 µm thickness GaSe crystals are used for generation and detection, respectively.

This work was performed, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. #158883

8845-30, Session 6

Ultrafast spectroscopy of hot electron and hole dynamics in GaP

Christopher M. Collier, Brandon Born, Xian Jin, Jonathan F. Holzman, UBC Okanagan (Canada)

Wide-bandgap semiconductors are appealing materials for photoconductive applications with large photon energies and high intensities. GaP is an excellent example of this and has received a recent resurgence in interest for applications such as terahertz (THz) generation, due to its excellent epitaxial growth properties and high optical phonon resonances (above 11 THz). Recently, Dietze et al. [Dietze, Opt. Lett., 2012] have, for example, made use of multiphoton nonlinearities in GaP for dynamic phase-tuning and efficient THz generation. Hot phonons are proposed as the nonlinear phase-tuning mechanism of GaP, although there is little understanding in the literature on the underlying ultrafast relaxation processes.

Given the interest in GaP, and the scarcity of knowledge on its ultrafast response, this work analyzes the femtosecond and picosecond carrier dynamics of GaP under intense photoexcitation. It is found that the dynamics are initially dominated by hot electron scattering to the X sidevalley from the central Gamma valley. Respective time constants of 800 fs and 4 ps are observed for transitions to the X7 and X6 valleys. A subsequent pump-fluence-dependent relaxation is observed over 30 to 52 ps timescales as pump fluence is increased. The prolonged energy relaxation is ascribed to impeded phonon decay in the X6 valley. Above and below a transition fluence value, distinct thermalization rate trends are observed. Experimental and theoretical results are shown to provide evidence for a hot phonon bottleneck at the high excitation fluences. The implications of these ultrafast carrier dynamics are discussed for emerging GaP applications.

8845-31, Session 7

Ultrafast four wave mixing holographic imaging *(Invited Paper)*

Yonggang Lu, Guanyu Liu, Peking Univ. (China); Kebin Shi, Peking Univ, (China)

Holography has been long known for its unique capability of retrieving both amplitude and phase of the heterodyne-recorded optical field. It has found important applications in three dimensional imaging and display since its inception. Original holographic imaging apparatuses have primarily been developed upon the linear contrast mechanisms as exemplified by linear scattering and reflection. On the contrary, nonlinearly generated signal from specimen is known to deliver more explicit information for better characterizing samples in various scientific fields such as biology and material research. Holographic imaging utilizing nonlinear contrast mechanism has been investigated recently. For example, holographic recording of second harmonic generation (SHG) from specimen's intrinsic structure or labelled nonlinear nano-crystal has been reported. The recorded holography enables full three dimensional field retrieval and phase conjugation imaging. Here we report on a nonlinear holographic imaging apparatus based on heterodyne recording of wide-field four wave mixing (FWM) signal. With Raman or surface plasmonic resonance enhancement, single shot recording with pulse duration of 22ps can be achieved. We will present our recent results on different categories of samples such as colloidal particles and metallic nano-rods. Techniques for non-resonant background suppression will also be discussed in this report.

8845-32, Session 7

High-speed volumetric fluorescence and nonlinear microscopy through phase-encoded axial position *(Invited Paper)*

Randy A. Bartels, Jeffrey J. Field, Colorado State Univ. (United States); Daniel J. Higley, Stanford Univ. (United States); David R. Smith, David G. Winters, Colorado State Univ. (United States)

Holographic imaging has gained favor in the biosciences for its rapid collection of volumetric data. While holography does not exhibit optical sectioning, and hence does not give true three-dimensional data, phase information encoded into a hologram means that it can be digitally re-focused to create a three-dimensional representation of the specimen. Digital holographic microscopy (DHM) with harmonic generation allows full three-dimensional reconstructions of the specimen. While these volumetric reconstructions have high fidelity with the specimen, a major limitation of standard DHM is that the contrast signal must be spatially coherent, ruling out fluorescence measurements, since the defocus phase cannot be measured directly. Instead, the signal originating from the specimen is made to interfere with a reference beam, and the resulting interferogram encodes the spatial phase information. However, by applying varied temporal modulations to the spatial extent of a line focus within the specimen, we show that the same spatial defocus phase is encoded into the spatially coherent illumination beam in spatial-frequency-modulated imaging (SPIFI), thereby relaxing the condition that the contrast signal be spatially coherent to perform volumetric reconstructions. Moreover, a key component of SPIFI is spatial

integration of the contrast intensity onto a single-element detector, encoding the spatial frequency content of the specimen in the resulting temporal signal. The combination of whole-field imaging and volumetric reconstructions at or beyond video rates makes fluorescent SPIFI an attractive alternative to slower volumetric techniques such as laser-scanning microscopy.

8845-33, Session 7

Multifocal multiphoton imaging and micro-machining with spatio-temporal focusing *(Invited Paper)*

Jeff A. Squier, Colorado School of Mines (United States)

Multifocal multiphoton imaging that enables the direct acquisition of three-dimensional volumes with single element detection is demonstrated. This system is capable of image acquisition rates of 30 frames per second, enabling capture of dynamic processes in volume. In addition, as a result of the novel detection scheme, weak signals such as harmonics can be detected simultaneously along with multiphoton fluorescence signals in a single detector without the use of frequency selective filters for the first time. In conjunction with this imaging system, a novel tissue ablation system has been developed that incorporates spatio-temporal focusing which enables precise ablation at fluences well above threshold. In many biological systems there is an ablation threshold disparity that complicates tissue cutting. An excessively tough region of tissue may mitigate the application of femtosecond ablation due to the increase in the ablation threshold. The approach detailed here over comes this limitation. Finally, this system will permit novel surgical implementations where low numerical apertures and long working distances are desired as a dictated by the geometry of the biological system.

8845-34, Session 7

Parallel axial imaging in scanning microscopy

Chuan Yang, The Pennsylvania State Univ. (United States); Kebin Shi, Peking Univ. (China); Mingda Zhou, Ding Ma, Venkatraman Gopalan, Shizhuo Yin, Siyang Zheng, Zhiwen Liu, The Pennsylvania State Univ. (United States)

In conventional scanning optical microscopy, several techniques have been developed to realize high-speed scanning in lateral (x-y) dimensions. However, to achieve 3-D microscopic imaging, slow mechanical scanning of the objective lens or the specimen itself in the z direction is typically required, which impedes the development of the capability for imaging fast processes in the axial direction. We discuss a method for effective axial scanning, in which chromatic aberration is exploited to focus different wavelengths of an excitation beam into different axial positions, and demonstrate parallel axial imaging in both second harmonic microscopy and two-photon fluorescence microscopy. In second harmonic (SH) microscopy, SH signals with different doubled frequencies can be generated at different axial positions, and can therefore be detected in parallel by using a spectrometer, while in two-photon fluorescence imaging, an array of 45°-tilted micro mirrors is used to reflect fluorescence signals emitted from different depths of the specimen onto an image sensor for parallel detection. Both experimental results and numerical analysis will be presented.

8845-35, Session 8

Simplified two-beam hybrid fs/ps CARS demonstrated in 1D and 2D *(Invited Paper)*

Christopher Kliewer, Sandia National Labs., California (United States)

We explore a novel phase matching scheme for gas-phase rotational coherent anti-Stokes Raman spectroscopy (CARS). The scheme significantly simplifies the employment of the technique in general. Two laser beams, one broadband and one narrowband, are crossed at arbitrary angle and the generated rotational CARS signal, copropagating with the probe beam, is isolated using a polarization gating technique. The effect of phase-vector mismatch for various experimental implementations was measured experimentally and compared to calculations. The spatial resolution of the current technique is improved by more than an order of magnitude over standard gas-phase CARS experimental arrangements, providing an interaction length of less than 50 µm when desired. Both the pump and Stokes photons originate from the broadband pulse, and are therefore automatically overlapped temporally and spatially. Significantly improved signal levels are achieved because of both the ease of alignment and the higher pulse energy available to the pump and Stokes fields. We demonstrate the technique for single-laser-shot 1D RCARS signal generation over approximately a 1 cm field in a flame. Perhaps most importantly, the novel phase-matching scheme enables the generation of CARS signals in 2D within a single laser shot. Such spatially correlated data is of high importance for relating experimental measurements to high-fidelity numerical simulations of combustion, for instance.

8845-36, Session 8

Femtosecond Raman force spectroscopy *(Invited Paper)*

Eric O. Potma, Dmitry Fishman, Junghoon Jahng, Jordan Brocious, H. Kumar Wickramasinghe, Jon Burdett, Fei Huang, Univ. of California, Irvine (United States)

In a conventional stimulated Raman scattering (SRS) measurement, changes in photon occupation number of the incident pump and Stokes beams are measured in the far-field, which reports on successful Raman transitions in the molecules in focus. However, detecting stimulated Raman transitions grows exceedingly more challenging when approaching the single molecule limit, as the change in the photon occupation number becomes significantly lower than the magnitude of the intrinsic Poisson noise of the incident beams. Direct measurement of successful Raman transitions in the near field through non-optical detection can avoid the unfavorable photon statistics that complicate far-field SRS measurements in this low copy number limit.

One non-optical detection approach is based on monitoring light-induced changes in the attractive force between a dipole and its corresponding image in a metal tip. Any optical transition, including Raman transitions, may bring about change in the local image force, which can in turn be measured with a cantilevered tip. When frequency modulating both the pump and Stokes beams, Raman induced changes in the image force can be detected in the cantilever mechanical response at the difference frequency of the modulation. This principle was recently shown for the case of continuous light illumination. In this work, we demonstrate that this method can be extended to the case of femtosecond SRS. We show that time-resolved pump-probe and Raman induced transitions can be measured with the femtosecond Raman force microscope in molecules present at low copy numbers.

8845-37, Session 8

Coherence in UV resonance Raman spectroscopy of liquid benzene and toluene *(Invited Paper)*

Hans D. Hallen, North Carolina State Univ. (United States); Adam H. Willitsford, Johns Hopkins Univ. Applied Physics Lab. (United States); C. Todd Chadwick, C. Russell Philbrick, North Carolina State Univ. (United States)

We have measured UV resonance Raman near and at the resonance absorption lines of liquid benzene and toluene. Resonance absorption with excitation on the symmetry-forbidden but strongly phonon coupled 1B2u band, ~230-270 nm, presents enhancement according to the vapor phase absorptions rather than those of the liquid phase. This effect is related to the coherence forced by the internal molecular resonance required to absorb light at this energy. The resonance gains (~1000x) are larger than expected due to the narrower vapor phase lines. Several multiplets and overtone modes are enhanced along with the strongly-coupled ring breathing mode.

8845-38, Session 8

Raman spectroscopic sensing using whispering gallery microresonators

Perry S. Edwards, Corey Janisch, The Pennsylvania State Univ. (United States); Bo Peng, Lan Yang, Washington Univ. in St. Louis (United States); Zhiwen Liu, The Pennsylvania State Univ. (United States)

We investigate resonator enhanced Raman spectroscopy as a label-free method toward single particle sensing. Whispering gallery mode microresonators are used as platforms to perform sensitive particle detection by exploiting the strong, evanescent field of a resonant mode exposed on the surface of the microresonator. Particles adhered to the microresonator surface interact with the field and inelastically scatter photons circulating within the resonator. In particular, Raman scattered photons are detected, providing molecular-specific “fingerprint” information regarding the adhered particles. The exploitation of a resonant mode allows for enhancement of generated Raman signal over traditional methods of spontaneous Raman scattering. Experimental results will be shown demonstrating the resonator enhancement.

8845-39, Session 8

High-speed coherent Raman imaging (CRI) of cells and tissues with broadband coherent anti-Stokes Raman scattering (BCARS)

Charles H. Camp Jr., Young J. Lee, Christopher M. Hartshorn, Marcus T. Cicerone, National Institute of Standards and Technology (United States)

Raman microspectroscopy is a powerful tool for the analysis of chemical species within biological samples, but with pixel dwell times on the order of seconds to minutes, its use as a high-throughput imaging modality is limited. We present our development of a high-speed coherent Raman imaging (CRI) microscope based on broadband coherent anti-Stokes Raman scattering (BCARS) that utilizes fiber laser sources and a CMOS camera-equipped spectrograph allowing pixel rates down to 160 microseconds with spectra spanning approximately 480 – 4550 cm-1. The system utilizes two fiber laser sources (a 1.5 ps probe source and a 16 fs compressed supercontinuum source) emanating from the same mode-locked seed source that provides attosecond synchronization, high system stability, and ~11 cm-1 spectral resolution in a compact footprint. Additionally, the intrapulse Raman excitation from the supercontinuum source generates strong spectral response within the fingerprint region, especially at low wavenumbers. Although the use of extremely short laser excitation pulses leads to a dramatic enhancement in the nonresonant background (NRB), the use of a modified Kramers-Kronig algorithm provides background-free Raman response extraction with extremely high numerical efficiency. This system provides a platform for high-speed, broadband CRI that opens up the practical application to live cells, tissues, and high throughput screening. To demonstrate these achievements, we will present chemical imaging of brain and cancer tissues with morphological and spectral signatures, as well as, cultured cells with chemically identified organelles.

8845-40, Session PMon

Diagnosis of liver disease using a multimodal multiphoton optical microspectroscopy image

Jang Hyuk Lee, Jong Chul Kim, Giyoong Tae, Myoung-kyu Oh, Do-Kyeong Ko, Gwangju Institute of Science and Technology (Korea, Republic of)

Liver fibrosis is characterized by the excessive accumulation of extracellular matrix (ECM) proteins including collagen, which occurs in most types of chronic liver diseases. Our goal is to develop multimodal multiphoton nonlinear optical microspectroscopy imaging system and efficiently investigate the fibrotic liver disease by multimodal images and coherent anti-Stokes Raman scattering (CARS) spectrum. CARS microspectroscopy was integrated with other multiphoton microscopy techniques, two-photon excitation fluorescence (TPEF) and second harmonic generation (SHG) microscopy, in one platform. It was applied to liver disease samples such as liver fibrosis tissue and cirrhosis. As a result, normal and liver disease sample were exactly distinguished because of the great difference by CARS spectra as well as multimodal multiphoton nonlinear optical images. A few collagens and hepatic lipid droplets were observed in normal tissue while a lot of aggregated collagen fibers and hepatic lipid droplets were clearly visualized in liver disease tissue by SHG and CARS microscopy images, respectively. We expect the system as a great early diagnosis tool for liver fibrosis by detecting an early stage of liver disease at tissue level.

8845-41, Session PMon

Portable multispectral imaging system for oral cancer diagnosis

Yao-Fang Hsieh, National Central Univ. (Taiwan); Mang Ou-Yang, National Chiao Tung Univ. (Taiwan); Cheng-Chung Lee, National Central Univ. (Taiwan)

This study presents the portable multispectral imaging system that can acquire the image of specific spectrum in vivo for oral cancer diagnosis. The system can acquire the spectral and spatial information simultaneously. According to the research literature, the autofluorescence of cells and tissue have been widely applied to diagnose oral cancer. The spectral distribution is difference for lesions of epithelial cells and normal cells after excited fluorescence. We have been developed the hyperspectral and multispectral techniques for oral cancer diagnosis in three generations. This research is the third generation. The excited and emission spectrum for the diagnosis are acquired from the research of first generation. The portable system for detection of oral cancer is modified for existing handheld microscope . The UV LED is used to illuminate the surface of oral cavity and excite the cells to produce fluorescent. The image passes through the central channel and filter out unwanted spectrum by the selection of filter, and focused by the focus lens on the image sensor. Therefore, we can achieve the specific wavelength image via fluorescence reaction. The specificity and sensitivity of the system are 85% and 90%, respectively.

8845-42, Session PMon

Upconversion of infrared radiation in PbSe/CdSe core-shell colloidal quantum dots

Nikolay S. Makarov, Qianglu Lin, Weon-Kyu Koh, Victor I. Klimov, Los Alamos National Lab. (United States)

Large two-photon absorption cross sections are of immediate interest for various applications including volumetric optical memory, three-dimensional microscopy, optical power limiting, photodynamic therapy, and solar energy conversion. Core-shell colloidal quantum dots are optimal for engineering of large two-photon absorption cross sections due to solution-based processibility of these nanomaterials and fairly

straightforward manipulation of optical resonances by varying the dimensions of the core and the shell independently from each other.

Here, we have examined a series of PbSe/CdSe core-shell colloidal quantum dots of various sizes (shell thickness 1 3 nm and core diameter 4 8 nm). All of these samples show dual emission with the infrared band due to PbSe-core and the visible band originating from the CdSe shell. We have measured two-photon absorption cross sections of the quantum dots by monitoring visible up-converted emission, excited with the infrared fs laser pulses that are in the range of optical absorption of the PbSe core. Quadratic dependence of the visible emission intensity on excitation power confirms a two-photon excitation mechanism. The measured two-photon absorption cross sections are about one order of magnitude larger than those of core-only CdSe quantum dots and reach up to ~2x10^6 GM for apparent values and ~3x10^7 GM for the values corrected for the local field factor. We explain such an increase in the cross sections by resonance enhancement due to core absorption. We have also examined a possibility of Auger-assisted up-conversion in samples with smaller core sizes and thicker shells. Our study demonstrates that the use of core/shell structures represents a promising approach for obtaining enhanced two-photon absorption cross-sections.

8845-43, Session PMon

1D-scanning addressable multiregional multifocal multiphoton microscopy

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Multiphoton laser scanning microscopy is capable of three-dimensionally imaging thick specimens with high resolution without confocal pinholes. But due to the low scanning rate, it cannot be applied to imaging samples with dynamic behavior. One of the first methods designed to improve scanning rate is line scanning, in which the excitation laser is focused with a cylindrical lens to create a line focus on the sample plane, making one of the two lateral scans unnecessary. Line focus can, however, cause cross-talk because of the lack of confocal gates. Interference on out-of-focus planes occurs between adjacent points when they are too close, degrading the resolution of the imaging system. In this study, we developed a novel addressable multiregional multiphoton microscope that employs a fast one-dimensional discrete-line scanning approach based on a spatial light modulator (SLM). The phase-only SLM shapes an incoming mode-locked, near-infrared Ti:sapphire laser beam into multiple specific discrete-lines, which are designed according to the sizes and locations of the target samples. Only the target-sample areas are scanned one-dimensionally, resulting in an efficient use of the laser's power. Compared with conventional multiphoton microscopies, this technique shortens scanning time and minimizes photodamage by concentrating scanning energy and dwell time on the areas of interest. This increase of imaging speed is critical for recording very fast process of live samples. Additionally, our discrete-line-focus design eliminates the cross-talk that occurs in conventional one-dimensional line-scanning multiphoton microscopes, thus enhancing the lateral and axial resolutions of the line-scanning imaging system.

8845-44, Session PMon

Spectroscopic assessment of the water molecule in liquid state valent angle

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Our research is devoted to the vibrational spectroscopy inverse problem solution that gives a possibility to make conclusions about the investigated molecule geometry, in particular an assessment of water molecule in the liquid state valent angle.

3N-matrix method was applied to solve the inverse vibrational spectroscopy problem. There is an ability to make no assumption about the molecule force field. An anharmonicity of both characteristic and noncharacteristic vibrations always exists so there is a reason to do a correction caused by the anharmonicity. For this purpose, the formula

??0i= ??i(1+ui ??i)

was used, where ??I is the frequency that is determined experimentally, ??0i is the zero vibrations frequency, and ui is an anharmonicity constant analogue. Taking molecules interaction into account made it possible to insert noncharacteristic vibration frequencies into calculations. The 3N-martix method use simplifies u3 constant calculating. Finding u1 and u2 values was our next step.

Analytic expressions for force matrix elements permitted to find the matrix explicit form. This matrix was used to solve the direct vibrational spectroscopy problem. Found normal characteristic vibrations frequencies were compared with those ones determined experimentally using divergence parameter. The formula

y=(1-??1,theor/??1,exp)2+(1-??2,theor/??2,exp)2+(1-??3,theor/??3,exp)2

was used to define the divergence parameter. ??theor is a calculated theoretically frequency, ??exp is a measured experimentally frequency. The defined divergence parameter is a function of valent angle ??. The valent angle assessment was reduced to the divergence parameter minimization. The ?? value concerning divergence parameter minimum was interpreted as a desired valent angle. According to all assumptions ??=89°.

8845-45, Session PMon

Optical parametric oscillators synchronously pumped by fundamental and second harmonic radiation of femtosecond Yb:KGW laser

Karolina Stankevi?i?t?, Ieva Pipinyt?, Julius Vengelis, Vilnius Univ. (Lithuania); Rimantas Grigonis, Vilnius Univ. (Lithuania) and Light Conversion Ltd. (Lithuania); Robert C. Eckardt, Gooch & Housego, Cleveland (United States); Valdas Sirutkaitis, Vilnius Univ. (Lithuania)

There are many applications where ~75 MHz repetition rate continuously tunable femtosecond pulses are needed. In such cases synchronously pumped optical parametric oscillators (SPOPOs) pumped by continuous trains of femtosecond pulses ? have to be used. Today most commercially available SPOPOs are pumped by first or second harmonics of femtosecond Ti:sapphire lasers, but in the past five years femtosecond Yb:KGW lasers systems emerged in industry and research facilities. This gives an opportunity to create compact, more efficient and cheaper continuously wavelength tunable ultrashort pulse systems with pulse durations from ~100 fs to ~3 ps. In this report we present results obtained during investigation and construction of SPOPO's pumped by fundamental (1030 nm) and second harmonic (515 nm) of Yb:KGW laser providing 105 fs pulses at 76 MHz repetition rate with average output power 4 W and 2.4 W at 1030 nm and 515 nm wavelength, respectively. BBO and BiBO nonlinear crystals were tested in SPOPO pumped by 515 nm pulses in order to achieve wavelength tuning in 630 – 2000 nm range. For wavelength tuning in 1400-4000 nm range PPLN crystal was tested in SPOPO pumped by 1030 nm pulses. Wavelength tuning capabilities via rotation of nonlinear crystal, SPOPO cavity length or PPLN grating period variation were investigated. Generation thresholds and output powers at different signal wavelengths were determined in SPOPO cavities with and without dispersion compensation.

8845-46, Session PMon

Performance evaluation of hybrid VLC using device cost and power over data throughput criteria

Chia Ching Lee, Ching Seong Tan, Hin Yong Wong, Multimedia Univ. (Malaysia); M. B. Yahya, TM R&D (Malaysia)

Visible light communication (VLC) technology has been gaining attention in both academia and industry recently. It is driven by the progress of light emitting diode (LED) technology for solid-state lighting (SSL). It has great potential to gradually replace radio frequency (RF) wireless technology as it offers huge, unregulated, unlicensed bandwidth to cope with future demand of indoor wireless access to real–time bandwidth-intensive applications. However, it was found to provide intrusive uplink channel that give rise to unpleasant irradiance from the user device which could interfere with the downlink channel of VLC and hence limit mobility to users as a result of small coverage (field of view of VLC).To address this potential problem, a Hybrid VLC system which integrates VLC (for downlink) and RF (for uplink) technology is proposed. It offers a non-intrusive RF back channel that provides high throughput VLC, maintains durability with conventional RF devices, and demonstrates excellent scalability .To deploy Hybrid VLC system in the market, it must be energy and cost saving to attain its equivalent economical advantage by comparing to existing architecture that employs fluorescent or LED lights with RF technology. In this paper, performance evaluation on the proposed hybrid system was carried out in terms of device cost and power consumption against data throughput. Based on our simulation ,Hybrid VLC system was found to reduce device cost by 3% and power consumption by 68% when compare to fluorescent lights with RF technology . Nevertheless, when it is compared to LED lights with RF technology, our proposed hybrid system is found to achieve device cost saving as high as 47% and reduce power consumption by 49%. Such promising results have demonstrated that Hybrid VLC system is a feasible solution and has paved the way for greater cost saving and energy efficient compares with the current RF architecture even with the increasing requirement of indoor area coverage.

8845-47, Session PMon

Enhanced optical second-harmonic generation from current-biased graphene on a SiO2/Si(001) substrate

Yong Q. An, Je-Ung Lee, Alain C. Diebold, Univ. at Albany (United States)

Recent theoretical calculations have predicted that electrically biased graphene can be a nonlinear optical material with giant nonlinearity. Experimental exploration of such giant nonlinearity is an important step toward implementing the electro-optical effect in graphene based devices. Field-effect transistors (FET) with graphene channels are suitable structures for nonlinear optical studies of graphene, because the graphene film in the channel region can be easily biased by an electric current or field and its transparency allows for nonlinear optical measurements. Nonlinear optical studies of graphene FET channels will elucidate new opportunities for combining high electron mobility with giant optical nonlinearity resulting in new optoelectronic devices. We have used a mm-sized FET-like graphene/SiO2/Si(001) structure to study the character and mechanism of electric current-induced second-harmonic generation (CI-SH) in graphene. We find that optical second-harmonic generation (SHG) in reflection from a chemical-vapor-deposition graphene monolayer on a SiO2/Si(001) substrate is enhanced about 3 times by the flow of direct electric current in graphene. Measurements of rotational-anisotropy SHG revealed that the CI-SH from the graphene/SiO2/Si(001) structure varies strongly by undergoing a phase inversion as the measurement location on graphene is shifted laterally along the current flow direction. Measurements of field-induced SHG on the graphene/SiO2/Si(001) structure and CI-SH on a graphene/glass structure indicated that the CI-SH enhancement is due to current-associated charge trapping at the graphene/SiO2 interface, which introduces an electric field across the SiO2/Si interface that produces field-induced SHG. The phase inversion is due to the positive-to-negative polarity switch of the trapped charges at the graphene/SiO2 interface.

Conference 8846: Terahertz Emitters, Receivers, and Applications IV

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8846-1, Session 1

Room temperature compact THz sources based on quantum cascade laser technology *(Invited Paper)*

Manijeh Razeghi, Northwestern Univ. (United States)

The terahertz (THz) spectral range is important for numerous applications in imaging, spectroscopy, and biological engineering. A compact, room temperature, tunable THz source is desirable for versatility and ease of integration. Thanks to recent development of high power mid-infrared (mid-IR) quantum cascade lasers (QCLs) and nonlinear mixing; a semiconductor THz source is realized with the same footprint of a mid-IR QCL, along with other features such as room temperature operation, electrical pumping, and wavelength tunability. We have demonstrated room temperature single mode THz emission across a wide frequency range of 1 – 4.6 THz. The highest THz output power is 180 ?W. By further optimizing the phase matching scheme, waveguide geometry, and pump powers, mW-level THz powers are projected at room temperature.

8846-2, Session 1

Injection schemes in quantum cascade lasers under operation *(Invited Paper)*

Martin Lindskog, David O. Winge, Andreas Wacker, Lund Univ. (Sweden)

The Quantum Cascade Laser (QCL) is a promising device for a large variety of THz applications. However up to date, the operation is limited to temperatures just below 200 K, as recently obtained by a device with a standard tunneling injection design [1]. In order to reach higher temperatures, the scattering injection scheme [2] appears promising, which was shown to operate under conditions, where the thermal energy widely exceeds the photon energy [3].

In our group, we have developed a simulation tool [4] based on nonequilibrium Green's functions, which allows for a quantitative modeling of QCLs taking fully into account quantum coherence. We provide recent examples of Terahertz QCLs with scattering [5] and tunneling [6] injection, where we can analyze the operation in detail. Based on our recent extension of the model to include high lasing fields [6,7], we show how the different injection schemes perform under lasing conditions.

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8846-3, Session 1

Terahertz quantum-cascade lasers with composite right/left handed metamaterial waveguides and antennas *(Invited Paper)*

Benjamin S. Williams, Amir A. Tavallaee, Philip Hon, Tatsuo Itoh, Univ. of California, Los Angeles (United States); Qisheng Chen, Northrop Grumman Aerospace Systems (United States)

The composite right/left-handed (CRLH) transmission line metamaterial has been used in the microwave frequency range to demonstrate novel guided wave and radiating devices, including leaky-wave and resonant antennas. CRLH structures exhibit a dispersion relation that supports backward-wave (left-handed) propagation, zero-index propagation, as well as forward-wave (right-handed) propagation. A CRLH transmission line metamaterial can be obtained by loading a conventional transmission line with series capacitance and shunt inductance. We have designed and implemented CRLH waveguides in THz quantum-cascade laser metal-metal waveguide, where series capacitance is obtained by adding capacitive gaps in the upper metallization and effective shunt inductance is obtained by operating in a higher order lateral mode. In this scheme, the GaAs/AlGaAs multiple quantum well quantum-cascade material is the dielectric of the transmission line – when properly injected with current it provides THz amplification via stimulated emission of photons due to intersubband radiative transitions. A CRLH leaky-wave antenna will radiate at an angle ?=sin-1 (?/k0), where ? is the propagation constant. We have demonstrated an active CRLH antenna fed by a THz quantum-cascade laser which can radiate in a backward, surface normal, or forward direction, depending upon the frequency of excitation. These CRLH metamaterial waveguides provide a flexible platform for future THz sources with advanced functionality, including frequency tuning, integrated phase/amplitude modulation, beam steering and shaping.

8846-4, Session 1

Quantum cascade lasers: a versatile and narrow-linewidth source in the terahertz range *(Invited Paper)*

Miriam S. Vitiello, Consiglio Nazionale delle Ricerche (Italy)

Quantum Cascade Lasers (QCLs) witness how materials engineering can actually forge objects that, with conventional technologies, could never exist. Being fully designed from scratch, they represent a powerful testing ground for fundamental properties relying on the quantum nature of the device.

Despite the cryogenic operation temperatures ($\leq$ 199.5 K), QCLs working in the far infrared have now a realistic chance to deeply impact technological applications, thanks to the high output power (>100mW), the quite broad operating frequency range (1.2-4.7 THz), the coherence and the compactness. Frequency- and phase-stabilized, high-power and reliable, solid-state terahertz sources can indeed find application in a large number of fields spanning from far-infrared astronomy and high-precision molecular gas spectroscopy, to high resolution coherent imaging and telecommunications, providing the carrier wave for broadband wireless links.

Experimental evidence of intrinsic linewidth (LW) values approaching the quantum limit in THz QCLs is here reported together with their potential in polarization spectroscopy experiments addressed to high sensitivity molecular detection. Highlighting the key role of the gain medium engineering, we demonstrate that properly designed semiconductor-heterostructure lasers could unveil the mechanisms underlying the laser intrinsic phase-noise, revealing the link between the device quantum properties and its quantum-limited LW.

In addition, recent results on the phase-locking of 2.5 THz QCLs to a free-space comb, generated in a $LiNbO_3$ waveguide and covering the 0.1–6 THz frequency range will be presented. The described approach paves the way to novel metrological-grade terahertz applications, including high-resolution spectroscopy, measurement of the absolute frequency, manipulation of cold molecules.

8846-5, Session 1

New materials and THz QCLs for radio-astronomy applications *(Invited Paper)*

Jérôme Faist, Keita Ohtani, Mattias Beck, Giacomo Scalari, Dana Turcinkova, Christofer B. Bonzon, ETH Zurich (Switzerland)

The quantum cascade laser (QCL) has demonstrated operation over an extremely wide wavelength range extending from the mid-infrared at 2.9?m to the Terahertz at 360?m. In addition, quantum cascade lasers operating in the mid-infrared have now demonstrated extremely high powers (>1W c.w.) with increasingly high wallplug efficiencies (>25%). These achievements require the design of very complicated sequences of layers with Angstrom accuracy.

In the terahertz, devices, taking advantage of the tight confinement provided by the metal-metal waveguide, we also have explored third order photonic wire lasers as well as photonic crystal quantum cascade lasers. In a further development, LC resonator cavities enable us to explore the coupling between transport and photon emission in the regime of very subwavelength emitters, as the ratio of volume over lambda cube is much below unity.

The present limitations of THz quantum cascade lasers to operation at temperature outside the reach of thermoelectric Peltier cooler has spurred new approaches that rely on different materials. We will discuss results from our group were we have worked on InAs and InGaAs – based materials with ternary and quaternary barriers. Laser devices with very low threshold current densities (<60A/cm2) have already been demonstrated.

In addition, we will discuss some recent results we have achieved at 4.7THz relevant for radio astronomy as well as the prospects for very tunable devices

8846-6, Session 2

Reconfigurable diamagnetic meta-molecules for broadband terahertz modulation *(Invited Paper)*

Mehmet Unlu, Christopher W. Berry, Mohammad R. Hashemi, Shang Hua Yang, Mona Jarrahi, Univ. of Michigan (United States)

Metamaterials offer a very promising platform for manipulating terahertz waves since their spectral response can be engineered by their geometry, rather than being limited by the characteristics of natural materials at terahertz frequencies. However, the operation bandwidth of the demonstrated metamaterial-based terahertz modulators has been limited by the resonant nature of the employed device configurations. Here, we present a broadband terahertz modulator based on a new class of reconfigurable meta-surfaces with switchable diamagnetic meta-molecules, which enables radical changes in the device scattering parameters over a broad range of terahertz frequencies. Switching the diamagnetic properties of the meta-molecules is made possible through changing their structural configuration by integration of the meta-surface structure with an array of electrostatically actuated MEMS switches. In contrast to the previously demonstrated MEMS-reconfigurable terahertz metamaterials, the electromechanical displacement required for structural reconfiguration is less than 250 nm in the presented terahertz meta-surface, enabling device operation at low modulation voltages and high modulation speeds. We experimentally demonstrate more than 70% modulation depth over a 1.5 THz frequency band, under a modulation voltage of 30 V and modulation speeds exceeding 20 KHz. The achieved modulation depth is the highest reported among previously demonstrated terahertz intensity modulators, in general, and 5 times higher than the demonstrated broadband terahertz modulators with similar modulation voltages and modulation speeds, specifically.

8846-7, Session 2

Gradient index devices for terahertz waves and terahertz surface waves *(Invited Paper)*

Marco Rahm, Martin Volk, Tassilo Fip, Jens Neu, Michael Höh, Benjamin Reinhard, Technische Univ. Kaiserslautern (Germany)

Gradient index (GRIN) optics has a long-term history that originates from ideas that were developed in the 19th century by Maxwell. While most of these concepts could not be put into reality due to a lack of suitable electromagnetic media, the birth of metamaterials in the late 90s enabled the practical implementation of such devices in an unprecedented manner.

Here, we demonstrate a variety of GRIN devices for both freely propagating terahertz waves and terahertz surface waves. As specific examples of static GRIN optics we experimentally investigated and measured the optical properties of a focusing terahertz GRIN lens with sub-wavelength focusing capabilities. Moreover, we devised and fabricated a terahertz beam deflector with a maximum deflection angle of 4.2 deg. The thickness of the beam deflector was only about 100 µm which is sub-wavelength at a frequency of 1.3 THz. In this context, we also discuss various concepts for the design and implementation of adaptive GRIN optics with tunable optical properties. For example, we theoretically investigated and optimized an approach that is suitable for the fabrication of a focusing terahertz GRIN lens with variable focus length and focus size.

Another intriguing concept is the use of specifically designed meta-surfaces that support strongly confined terahertz surface waves. We show that the surface waves can be deliberately guided within the plane of propagation by use of GRIN structures. For example, we evidenced the focusing behavior of a meta-surface GRIN lens by near-field mapping of the terahertz field.

8846-8, Session 2

Coupled polaritons and antipolaritons in dispersive gain media

Mauro F. Fernandes Pereira Jr., Sheffield Hallam Univ. (United Kingdom)

In this paper we predict how a material excitation with a dispersive gain profile couples with light in a microcavity. We show that even a single transition yields an interacting set of coupled intersubband polariton [1] and antipolariton [2] branches which can potentially lead to a new level of all-optical control and switching in a microcavity. In contrast to the conventional antipolariton case with an imaginary Rabi frequency, the dilute nitride quantum wells chosen [3] show ample flexibility to engineer the dispersive gain shape without global inversion and have potential for real Rabi frequencies with measurable oscillations, suggesting this as the medium of choice to investigate the coupling of photonic modes with an excitation delivering dispersive gain.

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8846-9, Session 2

Scattering of terahertz radiation in thin layers of dielectric materials

Irina Fokina, Kirill I. Zaytsev, Valeriy E. Karasik, Stanislav Yurchenko, Konstantin P. Tsapenko, Bauman Moscow State Technical Univ. (Russian Federation)

Terahertz radiation is used for different applications including time-domain spectroscopy, diagnostics of human tissue diseases, nondestructive test of composite materials, identification of drugs and explosives. Since it is important to obtain spectroscopic information in all these applications, there is a specific interest in studying processes of reducing useful information.

Spectral characteristics of inhomogeneous medium are distorting because of scattering inside this medium. In another case if a medium of interest is covered by another material, which is considered to be transparent for THz radiation, a received signal is scattered in this covering layer.

In this work scattering of THz radiation in thin layers of dielectric material was studied. Particularly, fabric materials were chosen. Scattering was modeled by the use of numerical solution of Maxwell equations by using the finite-difference time domain method. For modeling the structure of fabric, a model of infinite cylinders array was considered. Scattering cross-section and indicatrix were obtained. Then spectral transmittance was computed.

During a set of experiments THz spectral transmittance of various fabric materials were obtained. These experiments showed that for purpose of designing THz visual system for detecting concealed under clothes objects it is essential to select working frequencies lower than 1 THz.

Confrontation of the numerical and experimental results was carried out.

The developed method for obtaining scattering characteristics of different materials can be used for extracting useful information from received THz signal.

8846-10, Session 2

Ultra-strong light-matter interaction with mid-infrared metamaterials *(Invited Paper)*

Alexander Benz, Sandia National Labs. (United States); Salvatore Campione, Univ. of California, Irvine (United States); Sheng Liu, Ines Montano, John F. Klem, Michael B. Sinclair, Sandia National Labs. (United States); Filippo Capolino, Univ. of California, Irvine (United States); Igal Brener, Sandia National Labs. (United States)

Ultra-strong coupling is a new regime of light-matter interaction and a highly active field of research. In this regime the energy exchange rate between an optical cavity and a two-level system becomes similar to the fundamental system oscillation itself. One of the immediate outcomes is the non-classical nature of the ground state being squeezed vacuum containing only a finite number of virtual photons.

Here, we present experimentally the strong light-matter coupling of a metamaterial mode and an intersubband transition (ISTs) in the mid-infrared (MIR) spectral range. We use a conventional two-dimensional metallic meta-surface processed on top of semiconductor heterostructures designed with ISTs around 10 um. Upon tuning, the single resonance splits into the two polariton branches; the maximum splitting reaches 15% of the central frequency. Additionally, we have also measured the ultra-fast energy exchange directly using a novel time-domain spectroscopy system. We can observe clearly the Rabi oscillation with a period of 480 fs, corresponding to a Rabi frequency of 2.1 THz. We will further discuss a new strong coupling formalism that takes into account many body effects and strong exciting light fields.

This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. #158883

8846-11, Session 3

Room-temperature terahertz oscillation of resonant tunneling diodes *(Invited Paper)*

Masahiro Asada, Safumi Suzuki, Tokyo Institute of Technology (Japan)

Our recent results of a room-temperature THz oscillator using a resonant tunneling diode (RTD) are reported. This oscillator is composed of a GaInAs/AlAs double-barrier RTD and a planar slot antenna. The maximum frequency of oscillation in RTDs is limited by the delay time of electrons across the RTD layers, which consists of the dwell time in the resonant tunneling region and the transit time across the collector depletion region. The dwell time was reduced by a narrow well, and a fundamental oscillation up to 1.31 THz with the output power of 10 microwatts was achieved at room temperature. For further increase in oscillation frequency, we proposed a composite collector structure for the reduction of collector transit time. In this structure, the electron transition between the gamma and L conduction bands, which causes a long transit time, can be suppressed, and a fundamental oscillation up to around 2 THz is theoretically possible. For high output power, coherent power combining was demonstrated in a two-element array with offset slot antennas coupled with each other, and 610 microwatts at 620 GHz was obtained. Spectral characteristics were measured with a heterodyne detection, and the linewidth of less than 10 MHz was obtained. 1-5 percent frequency change with bias voltage was also observed, which is attributed to the bias-dependent dwell time. Direct intensity modulation with bias voltage and wireless data transmission were demonstrated. A transmission rate of 3 Gbps with the bit error rate of 3e-5 was obtained at 540 GHz in a preliminary experiment.

8846-12, Session 3

THz sources using indium phosphide high electron mobility transistors *(Invited Paper)*

William R. Deal, Northrop Grumman Corp. (United States)

THz power generation has long limited the types of practical applications at THz frequencies. With new improvements in maximum frequency of oscillation (fMAX), integrated circuits can now be realized which multiply and then amplify signals at frequencies approaching 1 THz. An overview in Northrop Grumman's technical progress at realizing THz sources will be presented.

8846-13, Session 3

Terahertz emitters based on impurity transitions in semiconductors *(Invited Paper)*

James Kolodzey, Univ. of Delaware (United States)

Terahertz emitters are important for fundamental studies in this interesting frequency regime and for applications ranging from medical diagnostics to see-through imaging. Although time domain emitters have the advantages of phase coherence and broad spectral range, the peak powers rarely exceed microwatts. Quantum cascade lasers can produce tens of milliwatts, but are complex with thousand of epitaxial layers. A much simpler approach is based on radiative transitions in neutral dopants and impurities in semiconductors. The dopants can be excited by an electrical current, or optically, and the THz emission occurs when the excited hydrogenic states relax toward the ground state. Both n-type and p-type dopants can be used for THz emission from many semiconductors including silicon. Unlike for conventional device applications, the dopants must not be thermally activated, however, which suggests deep dopant levels and/or low temperature operation. This application favors the wide bandgap semiconductors such as SiC and GaN, which can be incompletely activated even at room temperature, depending on the dopant. For example, electrically pumped THz emitters operating at temperatures over 250 K in pulse mode were

fabricated from nitrogen-doped SiC. The emission spectra had peaks from 5 to 12 THz (20 to 50 meV) that were attributed to electronic transitions of the nitrogen donors. These surface-emitting devices produced a peak power density at 77 K of 60 milliwatt/sq.-cm, which is suitable for a wide range of high power THz applications. We will report on the characteristics and limitations of dopant-based THz emitters from several semiconductor systems.

8846-14, Session 3

Broadband photonic terahertz-wave emitter based on planar-antenna-integrated UTC-PD *(Invited Paper)*

Hiroshi Ito, Kitasato Univ. (Japan); Toshihide Yoshimatsu, Nippon Telegraph and Telephone Corp. (Japan); Tadao Ishibashi, NTT Photonics Labs. (Japan)

Photomixing is a promising technique for generating continuous terahertz (THz) waves since it offers extremely-wide frequency tunability, very narrow line-width, and the capability of low-loss signal transmission through flexible optical fibers. Especially, the use of long-wavelength (1.55-um-band) light is practically important. The uni-traveling-carrier photodiode (UTC-PD) is a promising solution for such requirements. The UTC-PD has a unique mode of operation where only electrons are the active carriers. This is the key to achieving high speed and high saturation output current simultaneously.

To fully utilize the features of the UTC-PD for the THz-wave generation, monolithic integration of a proper planar antenna is indispensable. Among several antennas, the self-complementary (SC) antenna is one of the best solutions for the signal transmission over the wide-frequency-range from single device, because its input impedance is independent of the source frequency. We fabricated devices integrating several types of SC antennas, and assembled them in quasi-optical packages. Although all the modules exhibited broadband output characteristics up to 1.6 THz with similar output powers, the output characteristics at lower frequency side as well as their polarization characteristics were quite different. We could detect output powers from 30 GHz to 1.6 THz with almost constant polarization from a device integrating a novel compact planar antenna. Typical detected output powers were 120 uW at 200 GHz, 17 uW at 500 GHz, and 2.9 uW at 1 THz for a photocurrent of 10 mA with a bias voltage of only -0.6 V.

8846-44, Session 3

Semiconductor devices and electronics from microwaves to terahertz *(Invited Paper)*

Dimitris Pavlidis, Boston Univ. (United States)

Wide bandgap semiconductors, such as III-Nitrides and II-VIs, offer unique electronic and optical properties that make them suitable for a variety of applications ranging from communications to sensing. Components made with these materials operate from microwave-to millimeter-wave and THz frequencies. Signal generation and detection is particularly challenging at very high frequencies and new two- and three-terminal device approaches are being explored for this purpose. The talk will review various electronic device approaches, based on material, design, circuit implementation, processing and characterization considerations. These concepts pave the way to new families of components capable of responding to future electronic needs in the microwave to THz frequency regime.

8846-16, Session 4

Terahertz emission in polariton systems *(Invited Paper)*

Ivan A. Shelykh, Nanyang Technological Univ. (Singapore) and Univ. of Iceland (Iceland); Alexey V. Kavokin, Univ. of Southampton (United Kingdom)

We will consider several possible mechanisms of THz emission in polariton systems, namely:

1. We will show that planar semiconductor microcavities in the strong coupling regime can be used as sources of stimulated terahertz radiation. Emitted terahertz photons would have a frequency equal to the splitting of the cavity polariton modes. The optical transition between upper and lower polariton branches is allowed due to mixing of the upper polariton state with one of the excited exciton states and is stimulated in the polariton laser regime.

2. We will demonstrate that vertical cavity surface emitting terahertz lasers can be realized in conventional semiconductor microcavities with embedded quantum wells in the strong coupling regime. The cavity is to be pumped optically at half the frequency of the 2p exciton state. Once a threshold population of 2p excitons is achieved, a stimulated terahertz transition populates the lower exciton-polariton branch, and the cavity starts emitting laser light both in the optical and terahertz ranges. The lasing threshold is sensitive to the statistics of photons of the pumping light.

3. We will demonstrate the possibility of superradiant THz emission from dipolariton systems where resonant excitation of the cavity mode by a short pulse of light induces oscillations of the indirect exciton density with a characteristic frequency of Rabi flopping which generates . This results in oscillations of classical Hertz dipoles array which generate supperradiant emission on a terahertz (THz) frequency.

8846-17, Session 4

Highly efficient quantum dot-based photoconductive THz materials and devices *(Invited Paper)*

Ross R. Leyman, David J. Carnegie, Natalia Bazieva, Edik U. Rafailov, Univ. of Dundee (United Kingdom)

The THz optoelectronics field is now maturing and semiconductor-based THz devices are becoming more widely implemented as analytical tools in spectroscopy and imaging . Research into ultrafast semiconductor materials for THz devices is predominantly devoted to improving the optical-to-THz efficiency of photoconductive (PC) materials that generate THz signals when driven by suitable ultrafast coherent optical sources.

Materials traditionally used for this include low temperature-grown gallium arsenide (LT-GaAs) and LT-InGaAs for longer wavelength operation, and are used because the growth process integrates lattice defects and carrier trapping sites throughout the bulk, which act to shorten carrier lifetimes but also compromises carrier mobility and PC gain. We demonstrate here PC THz antenna devices comprising of GaAs/InAs quantum dot-based semiconductor structures, which utilise ultrafast carrier capturing offered by implanted InAs QDs to allow THz operation. This allows ultrafast optical pumping of the device with wavelengths absorbed by both/either the high quality GaAs crystal and/or InAs QDs, with high carrier mobility and almost arbitrarily short carrier lifetimes down to around 0.2 ps which is strongly determined by the pre-chosen QD layer periodicity .

We discuss such THz devices which exhibit optical-to-THz conversion efficiency around 5 times greater than commercial LT-GaAs-based devices.

8846-18, Session 4

Terahertz emitter based on dipolaritons

Oleksandr Kyriienko, Univ. of Iceland (Iceland) and Nanyang Technological Univ. (Singapore); Alexey V. Kavokin, Univ. of Southampton (United Kingdom) and St. Petersburg State Univ. (Russian Federation); Ivan A. Shelykh, Univ. of Iceland (Iceland) and Nanyang Technological Univ. (Singapore)

Dipolaritons are mixed light-matter quasiparticles formed in double quantum wells embedded into semiconductor microcavity. Here we study theoretically the effect of beats between dipolariton modes due to the tunnel coupling between direct and indirect excitons.

The model based on the Master equation for density matrix allows us to calculate dynamics of the system with accounting of decoherence effects using Lindblad approach. The combined tunnelling and cavity-exciton coupling effects result in Rabi flopping between two dipolariton modes and lead to harmonic oscillations of IX density. Since indirect excitons represent elementary dipoles, these density oscillations result in emission of THz frequency ranging from 1 to 4 THz. This mechanism of THz radiation is similar to downshift optical-to-THz frequency conversion used in laser driven terahertz emitters.

However, the system of dipolaritons has some important advantages over previously studied systems, namely: (1) the better tunability of the system allowing for fast modulation of the THz emission frequency; (2) improved spectral characteristics of THz signal which can be controlled using applied voltage and pumping conditions; (3) possibility to achieve a high output power as it is described below.

The essential difference of the generation scheme we propose from the previously studied schemes is in the use of the superradiance effect appearing due to the fact that Rabi oscillations in the dipolariton system are coherent. Rabi oscillations can be sustained by the cavity for several tens of picoseconds, which strongly improves the quantum efficiency of the emitter.

8846-19, Session 4

Bipolar THz-lasing structures based on InAs-GaSb coupled quantum wells as an alternative to intersubband lasing *(Invited Paper)*

Leonid D. Shvartsman, Boris Laikhtman, The Hebrew Univ. of Jerusalem (Israel)

Development of compact low-cost sources of a coherent radiation with a high efficiency in the range of several THz remains one of the key challenges of the modern security technologies. In spite of rather impressive achievements in intersubband quantum cascade lasers their current parameters are still far from the needs of practical implementation. We present here a bird-eye view on the current state of the field. We compare theoretical prospects of the optimal gain of lasers in the range of few THz for two cases: intersubband GaAs-based quantum cascade lasers and interband laser based on coupled quantum wells InAs-GaSb. We show that the last case promises the gain that could be three orders of magnitude higher.

Our methodology of such a comparison of two different systems that is reduced to the following. The most typical design of four-five subband multi-well GaAs-based QCL is compared with a typical InAs-GaSb coupled quantum well laser (CQWL) operating in the same frequency range. The detailed density matrix based calculation shows that the maximal possible gain for CQWL can be three orders of magnitude higher than for QCL while from the technological point of view QCLs , of course, still look much more attractive.

8846-20, Session 4

Tunable THz source using small parallel-connected superconducting tunnel junctions

Faouzi Boussaha, Alexandre Feret, Christine Chaumont, Observatoire de Paris (France); Lionel Loukitch, Institut National des Sciences Appliquées (France); Thibaut Vacelet, Observatoire de Paris (France)

We report on tunable submillimeter-wave radiation sources based on micrometer-sized superconducting tunnel junction arrays optimized within a bandwidth of 350-520 GHz. The arrays consist of 10, 20 and 40 Superconductor-Insulator-Superconductor (SIS) parallel-connected Nb/AlOx/Nb junctions embedded in superconducting microstrip lines. A SIS twin-junction is integrated along with each array to detect output signals. The pumped detector's I-V characteristic exhibits clearly photon-assisted quasiparticule steps when the arrays are biased upon corresponding Josephson resonances ranging from 370 to 520 GHz. We will present optimization and measurement results.

8846-21, Session 5

Nanotransistor based THz plasma detectors: low tempeatures, graphene, linearity, and circular polarisation studies *(Invited Paper)*

Wojciech Knap, Univ. Montpellier 2 (France)

Nanometer size field effect transistors can operate as efficient broadband terahertz detectors, far beyond their fundamental cut-of frequencies[1]. We present an overview of some important and recent results concerning the physics of THz rectification by nanometer scale field effect transistors. We report on temperature [2], power and polarization sensitivity studies [3] of these detectors.We report also on measurements of THz rectification by graphene field effect transistors[4] and they applications for THz communication[5].

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8846-22, Session 5

Field effect transistor as detector of THz radiation hélicity

Konstantin S. Romanov, Univ. Montpellier 2 (France); Christoph Drexler, Univ. Regensburg (Germany); Nina Diakonova, Univ. Montpellier 2 (France); Peter Olbrich, Johannes Karch, Michael Schafberger, Univ. Regensburg (Germany); Yuri A. Mityagin, P.N. Lebedev Physical Institute (Russian Federation); Dmytro B. But, Univ. Montpellier 2 (France); Oleg A. Klimenko, P.N. Lebedev Physical Institute (Russian Federation); Frederic Teppe, Wojtek Knap, Univ. Montpellier 2 (France); Sergey D. Ganichev, Univ. Regensburg (Germany); Mikhail I. Dyakonov, Univ. Montpellier 2 (France)

Field Effect Transistors (FET) have been demonstrated as promising detectors of THz radiation. Here we report on the experimentally observed and theoretically studied helicity dependent photoresponse of FETs.

We studied commercially available GaAs/AlGaAs HEMTs. For optical excitation we used molecular lasers providing single line tuneable radiation in the frequency range of f = 0.6 - 2.5 THz. Transistors were irradiated by elliptically, circularly, or linearly polarized radiation at normal incidence. Measurements were performed at room temperature.

We observed that with the increase of radiation frequency, the magnitude of the maximum of the response decreases, and at high frequencies, the signal switches its polarity at a certain gate bias. The photoresponse of FET to circularly polarized radiation strongly depended on the helicity of radiation. At some gate biases, the photoresponse even changed its sign with the switch from the right- to the left-handed circular polarization.

The phenomenon is interpreted in the frame of the generalized Dyakonov-Shur model. It results from the interference of plasma oscillations inside the FET channel. These oscillations are induced by antennas sensitive to different linear polarizations. The calculation shows that the helicity dependent response strongly depends on the length of FET and impedances of antennas. The obtained dependencies of photoresponse voltage on gate bias voltage qualitatively describe the experimental data. The results provide the basis for a new sensitive, all-electric, room-temperature and fast (better than 1 ns) characterisation of all polarization parameters of terahertz radiation.

8846-25, Session 6

Antenna-coupled microbolometer based uncooled focal plane array and camera for 2D real-time terahertz imaging *(Invited Paper)*

François Simoens, Jérome Meilhan, CEA-LETI (France)

CEA-Leti relied on its 20 year old know-how in thermal infrared bolometer to develop large monolithic focal plane arrays optimized for 2D real-time imaging in the terahertz range. A dedicated innovative bolometric pixel has been designed with an ongoing concern to achieve low cost devices both in fabrication and in use thanks to standard CMOS microelectronic processes and room temperature operation.

Specific structures of antennas and a resonant quarter-wavelength cavity are associated to a silicon bolometer microbridge: this architecture offers better than 10pW power detection threshold on the whole THz range by proper tailoring of the antennas while keeping the technological stack unchanged.

First prototypes of imaging arrays have been designed and manufactured for optimized sensing in the 2.5THz vicinity where THz quantum cascade lasers are delivering high optical power.

This paper first reports the latest results of performance characterizations where metrology conditions have been carefully carried out.

Then several tested implementations for real-time imaging applications are presented. In particular terahertz spectro-imaging techniques have been applied to concealed sugar pellets analysis with the use of a complete system developed by our institute. Real-time reflectance imaging of large surface of hidden objects has been demonstrated. High quality images of broadband THz beams delivered by a TDS system in the 0.1-2 THz range have shown the high interest of real-time 2D beam profiling.

Then perspectives of camera integration are discussed.

8846-26, Session 6

Discrete spectrum terahertz imaging using bow-tie diodes: optimized antenna designs and arrays

Gintaras Valu?is, Linas Minkevicius, Karolis Madeikis, Irmantas Ka?alynas, Rimvydas Venckevi?ius, Dalius Seliuta, Vincas Tamo?i?nas, Ctr. for Physical Sciences and Technology (Lithuania)

Discrete spectrum terahertz imaging using bow-tie diodes: optimized antenna designs and arrays

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Terahertz (THz) imaging is a powerful tool to observe packaged objects in various THz-radiation transparent materials like paper cartoon or plastic boxes. In order to indentify materials one needs to resolve spectral signatures at certain frequencies and improve recording system using multipixels arrays.

Recently, we have demonstrated that so-called InGaAs bow-tie diodes can successfully be used for terahertz direct and heterodyne imaging [1]. Employing broadband features of the device, spectra and images of plastic explosive simulators prepared from tartaric acid and sucrose were recorded within the frequency range of 0.585–2.52 THz [2].

In this work, we concentrate ourselves in optimization of InGaAs diodes operation at certain frequencies and demonstration of the bow-tie arrays performance.

Optimization routes were demonstrated using simulations based on 3D finite-difference time-domain method, calculating electromagnetic field amplitude ratio distribution in detector plane. Three types of designs – bow-tie diode itself, log-periodic antenna and log-periodic antenna coupled with the bow-tie diode were analyzed at frequencies of 0.3 THz and 0.6 THz. Enhancement of sensitivity nearly one order of magnitude is observed.

Terahertz imaging using multi-pixel arrays is demonstrated. Options for further improvements are discussed, implementation for real-time imaging applications is considered.

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8846-27, Session 6

Possibility of the passive THz camera using for a temperature difference observing of objects, placed inside the human body

Vyacheslav A. Trofimov, Vladislav V. Trofimov, Lomonosov Moscow State Univ. (Russian Federation)

We demonstrate the possibility of using of a passive THz camera for a temperature difference observing in the human skin if this difference is caused by different temperatures inside the body. We discuss two physical experiments, in which a person drinks hot and cold water. After computer processing of images captured by passive THz camera TS4 we may see the pronounced temperature trace on skin of the human body. We illustrate this phenomenon by a series of images captured by passive THz camera in real time.

As we believe, these experiments allow to increase field of passive THz camera using for the detection of objects concealed in the human body because the difference in temperature between object and parts of human body will be reflected on the human skin. However, modern passive THz cameras have not enough resolution in temperature to see this difference. That is why, we use computer processing to enhancethe camera resolution for this application.

We discuss also other modern problems of the THz passive camera using.

8846-28, Session 6

Experimental beam profiling and modeling of a terahertz beam generated from a 2-color air plasma

Pernille K. Klarskov, Andrew C. Strikwerda, Peter U. Jepsen, Technical Univ. of Denmark (Denmark)

As the steady advance of terahertz (THz) technology continues from research towards applied science, it is increasingly important to fully specify all characteristics of a given THz system. One of the more common THz generation techniques, due to its incredibly broad bandwidth, is that of nonlinear generation in a two-color air plasma. However, even though this technique has been widely used for several years, there have been few studies of the beam profile, and it was only published recently that the generated THz radiation propagates in a conical-like pattern due to an off-axis phase matching condition [You et al., Physical Review Letters, 109, 183902 (2012)]. To appropriately perform location dependent measurements such as imaging and z-scans, it is imperative to account for the spatially variant form of the THz waveform. Furthermore, it is beneficial to represent such an emission pattern in terms of well-understood propagating beam profiles.

Here we present our most recent results characterizing THz beams generated by two-color air plasmas. Using a THz camera (NEC IRV-T0831) and a pair of off-axis paraboloids, we experimentally measure the location dependent THz profile as it passes through a beam waist, similar to typical THz-TDS spectroscopy setups. We demonstrate that as the THz transient propagates through the beam waist, it tightens from the generated conical profile to a spot-like focus and eventually evolves back to a ring. This behavior is characteristic of Bessel-Gauss beams, and we qualitatively support this interpretation with numerical simulations.

8846-29, Session 7

Holography and phase retrieval in terahertz imaging *(Invited Paper)*

Nikolay V. Petrov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Andrei A. Gorodetsky, Foundation for Research and Technology-Hellas (Greece); Victor G. Bespalov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

In this talk we present review and latest results obtained in the scope of terahertz holographic and other methods for phase retrieval in terahertz imaging. Not only accurate change of amplitude, but also rigorous phase retrieval is essential for precise calculation of optical parameters of the samples in terahertz range.

Pulse terahertz holography introduced some years ago shows itself as perfect method for overall-object phase retrieval technique, but in the same time it allows measurement with low signal to noise that leads to less precise derivation of sample optical parameters. And certainly just point-by-point terahertz time-domain spectroscopy provides the most precise information of sample phase, but it is rather time consuming and has low spatial resolution as well.

The other possible way assumes, in contrary to pulse terahertz holography and spectroscopy, using narrowband CW terahertz source, which tunability might also make the measurement process easier. And diffraction patterns registered with microbolometer array or any other terahertz intensity sensor placed at several different distances from the object and/or taken for several different terahertz frequencies are used for phase retrieval in this case.

We present both numerical predictions and experimental results for the proposed methods, estimate the achievable spatial and other limits of the techniques, compare them to the others used in different spectral ranges and discuss future steps that are to be done in the scope of further improvements of existing terahertzphase retrieval techniques and possible new ways of full terahertz wavefront registration and use.

8846-30, Session 7

3D terahertz synthetic aperture imaging of objects with arbitrary boundaries

Gabriel P. Kniffin, Lisa M. Zurk, Scott Schecklman, Portland State Univ. (United States); Samuel C. Henry, Univ. of Washington (United States)

Terahertz (THz) imaging has shown promise for nondestructive evaluation (NDE) of a wide variety of manufactured products including integrated circuits and pharmaceutical tablets. Its ability to penetrate many non-polar dielectrics allows tomographic imaging of an object's 3D structure. In this work, we present advanced, physics-based THz synthetic aperture processing techniques which allow the 3D imaging and characterization of objects with one or more irregular boundaries.

In NDE applications, the material properties of the target(s) and background media are often well-known a priori and the objective is to identify the presence and/or 3D location of structures or defects within. The authors' earlier work demonstrated the ability to produce accurate 3D images of conductive targets embedded within a High Density Polyethelene (HDPE) background. That work assumed a priori knowledge of the refractive index of the HDPE as well as the physical location of the planar air-HDPE boundary. However, many objects of interest exhibit non-planar surfaces, such as varying degrees of curvature over the extent of the surface. Objects under test may also contain multiple stratified layers with differing refractive indices. Irregular boundaries between layers introduce refraction effects that distort 3D tomographic images.

In this work, a split-step Fourier migration method is applied to THz synthetic aperture processing to correct the artifacts introduced by irregular boundaries. The algorithm accurately detects the 3D location of the boundaries and provides high-resolution tomographic images of an object's internal structure. These techniques are demonstrated with measurements from a THz time-domain imaging system.

8846-31, Session 7

3D terahertz imaging *(Invited Paper)*

Patrick Mounaix, Univ. Bordeaux 1 (France)

Terahertz radiations can be seen as electromagnetic waves in the spectral range going from 0.3 to 10 THz. Low energy interaction of a wide range of materials can thus be studied by these waves and new data can potentially be retrieved to complete the knowledge of material. Terahertz technology has been making rapid progress following recent advances in femtosecond lasers and ultrafast semiconductor sources emitting in the THz frequency range. One of the most attractive properties of THz waves is their ability to pass through a wide variety of materials. They can be used to control or analyze through many types of packaging material. Moreover, the interaction with THz waves is non destructive, and thus these radiations can be used to probe fragile biological materials not only for basic research, but also for applications in a wide variety of fields.

More recently, the inventory of applications has increased to include, quality control, non destructive testing, and spectroscopic characterization .Two-dimensional THz transmission images were first acquired in 1995 by Hu and Nuss and sounded the beginning of 2D and 3D imaging science. Then a lot of research developments in terahertz imaging have made use of terahertz time-domain spectroscopy but also with numerous new efficient sources and detectors for continuous-wave terahertz radiation.

In the literature a number of methods for 3D imaging with THz radiation have been proposed and demonstrated. We will describe briefly different physical techniques capable to extract 3D information and we will analyze advantages and drawbacks of each method.

8846-32, Session 7

Terahertz imaging for medical applications *(Invited Paper)*

Joo-Hiuk Son, The Univ. of Seoul (Korea, Republic of)

Terahertz (THz) imaging is a promising modality for medical diagnosis because it is non-ionizing, sensitive to water molecules, and capable of spectroscopic analysis. In this presentation, various examples of medical imaging using THz radiation will be reviewed. First, the feasibility of THz dynamic imaging for visualizing serial changes in the distribution and penetration of a topical transdermal drug is demonstrated and compared with the Franz cell diffusion test. Secondly, some cases of cancer imaging using THz radiation are shown, which include brain tumor and oral melanoma. The THz imaging results are also compared with magnetic resonance (MR) imaging and conventional histology. Thirdly, the principle of terahertz molecular imaging (TMI) technique using nanoparticles is explained and the factors related to molecular imaging, such as sensitivity, resolution, and quantification property are characterized. The technique is applied to the diagnosis of cancerous tumors targeted with phase-conjugated nanoparticles and the distribution measurement of nanoparticle drug delivery to organs in vivo and ex vivo. Lastly, THz imaging is also utilized to analyze blood non-invasively. The THz complex optical constants of blood and its constituents such as water, plasma, and red blood cells (RBCs) are measured and used to extract the concentrations of RBCs. In conclusion, the author believes that there are some points where terahertz imaging can contribute to the real-world medicine.

8846-33, Session 8

The stable and intense broadband THz coherent synchrotron source at SOLEIL: performances and research program *(Invited Paper)*

Pascale Roy, Synchrotron SOLEIL (France)

The recent years have seen a significant development in Terahertz radiation production: moderate intensity broadband sources and higher power narrow band tunable sources. Although both types of sources allow significant breakthrough, only Coherent Synchrotron Radiation (CSR) combines the two advantages, providing a broadband and quite intense radiation in the THz domain. CSR occurs in electron storage rings when the wavefronts emitted by electrons within a bunch superimpose at equal phase. The resulting source power has a quadratic dependence to the number of electrons per bunch (typically 109) and can therefore reach several mW. The spectral range depends on the longitudinal shape of the electron bunch, but can be widened towards a few THz by reducing the bunch length. A third figure of merit, the source stability, which allows unprecedented signal to noise values and absolute intensity measurement is also clearly a strong point for CSR.

At the AILES beamline of SOLEIL synchrotron (France) the combined brilliance, stability and wide range (0.2-2 THz) achieved through this method has lead to an optimal use of FTIR in the THz range, hitherto unusable for demanding experiments. In particular, we are currently performing high resolution rotational studies of transient or reactive species, for which reducing the measurement duration is a prerequisite. The present measuring mode also allows an extension to the THz domain of near field subwavelength microspectrometry.

8846-34, Session 8

Probing of local electron states in Pb1-xSnxTe(In) narrow-gap semiconductors using laser terahertz radiation

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A new type of semiconductor local states is revealed in lead-tin telluride solid solutions doped with indium. The energy position of these states is not linked to any specific location in the semiconductor energy spectrum, but follows the quasiFermi level position, which may be tuned by photoexcitation. The binding energy of these states is less than 10 meV providing appearance of photoresponse at wavelengths exceeding 100 ?m. This conclusion is based on the results of experiments that use illumination of the samples by 100 ns – long pulses of a terahertz laser with the wavelengths of 90, 148 and 280 ?m.

We investigated photoconductivity in single crystals of Pb1-xSnxTe(In) with x varied within 0.22-0.29, and in highly degenerated polycrystalline PbTe(In) films. The persistent photoconductivity induced by the background radiation has resulted in generation of long-lived non-equilibrium electrons at low temperatures and, consequently, to formation of a quasiFermi level in the conduction band. The distance between the quasiFermi level and conduction band bottom depended on the alloy composition and reached its maximum of ~ 100 meV in PbTe(In) films. Tuning of the quasiFermi level position in PbTe(In) by means of an additional optical pumping allowed reducing conductivity by 20% of its initial value and to push the quasiFermi level position up by ~ 20 meV. No change of the relative photoresponse was observed for all of the laser wavelengths. It means that the local electron states remain in the close vicinity of the quasiFermi level even after it moves to another position.

8846-35, Session 8

Remote detection of nuclear materials using air breakdown ionization signatures *(Invited Paper)*

Phillip A. Sprangle, Univ. of Maryland, College Park (United States)

This paper presents a new concept for the remote detection of nuclear materials. This novel and advantageous detection method is based on air breakdown signatures in the vicinity of nuclear material and can enable stand-off detection at distances far greater than 100 m. Radioactive materials emit gamma rays which ionize the surrounding air. The free electrons produced by the gamma rays rapidly attach to oxygen molecules forming ions. In the vicinity of nuclear materials the density of ions and electrons is highly elevated compared to background levels. The enhanced levels of oxygen ions, which have a very low ionization potential, are a source of free electrons for inducing avalanche air breakdown. Air breakdown, i.e., spark formation, is driven remotely by high power THz or laser radiation or depending on stand-off distances and atmospheric conditions. The characteristics of the induced spark, e.g., breakdown rate, timing delay, duration and spectrum, are a direct signature of the presence of radioactivity. The rapid rise in electron density in the spark induces a detectable frequency modulation on a probe laser pulse which is also a detection signature.

8846-36, Session 8

Effective criterion for the detection and identification of explosive using the spectral dynamics analysis of THz reflected signal in real time

Vyacheslav A. Trofimov, Nikolay V. Peskov, Lomonosov Moscow State Univ. (Russian Federation)

One of the problems, arising in using of Time-Domain THz spectroscopy for the security, consists in developing of probability assessment criterion

for the detection and identification of the explosive and drugs. In present report we propose new effective criterion for finding the substance at using the reflected THz signal. This criterion consists of two steps. First step consists in preliminary definition of appropriate range of THz spectra of considered substances to detect the difference in spectral lines dynamics. The second step is a use of proposed integral estimation for the assessment of presence of required substance.

This approach was applied for distinguishing the substance with similar properties in the mixture. It is very important to stress that this criterion may be used in real-time.

8846-37, Session 8

THz intervalence antipolaritons

Mauro F. Fernandes Pereira Jr., Inuwa A. Faragai, Sheffield Hallam Univ. (United Kingdom)

In this paper we predict how a valence band excitation couples with TE-polarized THz radiation in a microcavity. This configuration would allow easier measurements of polaritons [1] and antipolaritons [2] without the need to grow the resonator in a slanted prism, as in usual TM mode, conduction band realizations. A Nonequilibrium Many Body approach delivering an optical response beyond the Hartree-Fock approximation allows the study of multiple transitions and an interesting picture of interacting polaritons and antipolaritons develops due to the coexistence of gain and cross absorption to higher subbands. The combination of bandnonparabolicity and nonequilibrium effects beyond the Hatree-Fock approximation plus microcavity coupling lead to further branches in the polariton spectrum that would not be expected with free carriers.

References

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8846-38, Session 8

Integrated diode technology for THz applications *(Invited Paper)*

Jan Stake, Huan Zhao, Vladimir Drakinskiy, Tomas Bryllert, Aleksandra Malko, Johanna Hanning, Aik Yean Tang, Chalmers Univ. of Technology (Sweden); Peter Sobis, Omnisys Instruments AB (Sweden); Robin Dahlbäck, Josip Vukusic, Chalmers Univ. of Technology (Sweden)

This paper provides an overview of research on terahertz integrated diodes and circuits carried out at Chalmers, Göteborg, Sweden. We will present progress on integration techniques for HBV multipliers and Schottky diode mixers and multipliers, including epitaxial transfer of III-Vs and heterogeneous integration on silicon. Moreover, we will present progress on THz device modelling and results from S-parameter characterization of on-chip components at terahertz frequencies. Finally, performance of mixer and multiplier demonstrators based on in-house technology will be presented.

8846-24, Session PMon

The dynamic range of THz broadband FET detectors

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The goal of this work was to study the capability of THz Field effect transistor (FET) detectors to measure high power radiation at frequencies from 0.3 to 3 THz and to determine the limits of linear detection. FETs are promising detectors of THz radiation. They have high responsivity, low noise equivalent power and fast response time.

We studied several type of HEMTs at the room temperature. To provide a wide range of incident THz radiation intensities we used different types of sources: i)continuos-wave: backward oscillators and CO2 pumped methanol laser ii) pulsed: NH3, D2O, and CH3F lasers and iii) the free electron laser (FEL) with pulses regime.

The nonlinear detection of THz radiation in FET had been predicted theoretically. According to the model the detection signal versus the radiation power should increase linearly changing gradually into square root like dependence. The linear effect and sublinear saturation were observed at different radiation frequencies in our experiments. In experiments with THz gas lasers we observed the linear dependence (up to about 1 kW/cm^2) followed by sublinear one in the range up to several I MW/cm^2. With FEL source at 2.11 THz with to extremely short pulses the photoresponse behaves differently: it increases close to the square of the power, saturates and then decreases slowly at the highest power levels.

We discuss the unusual behavior observed at high intensity experiments considering several phenomena: i) electron heating ii) impact ionisation or iii) response time effects related to extremely short pulses.

8846-39, Session PMon

The dependence of terahertz signal and third harmonic amplitudes on mutual polarization of two-color pump components under optical breakdown of air

Alexander Ushakov, Roman Volkov, Andrey Savel'ev, Lomonosov Moscow State Univ. (Russian Federation); Pavel Chizhov, Vladimir Bukin, Sergey V. Garnov, A. M. Prokhorov General Physics Institute (Russian Federation)

One of the methods to receive electromagnetic radiation in the terahertz range is the laser induced optical breakdown of gases (for instance, in the air under atmospheric pressure). In this scheme low-frequency radiation is created by the optical rectification process upon interaction of the femtosecond laser radiation at fundamental frequency with its second harmonic in a medium with cubic nonlinearity: ?_THz=2?-?-?. This process occurs due to a mechanism called "transient photocurrent" which takes place under ionization of air by the two-color field. This model provides a different dependence of the amplitude of terahertz signal than predicted by the structure of tensor of cubic nonlinearity. At the same time it is known that air breakdown is accompanied by the generation of the third harmonic. In this paper we decided to measure the dependence of the signal of the third harmonic and terahertz radiation on the mutual polarization of the first and second harmonic to compare the mechanisms of their generation. For this purpose we used the output radiation of laser system Spitfire pro with the following parameters: pulse duration 35 fs, central wavelength 800nm, repetition rate 1kHz, energy of the first and second harmonic are 2mJ and 240?J respectively. The radiation was focused by parabolic mirror with focal length 7,5 cm in air. The energy of terahertz and third harmonic radiation was measured by Holey cell and photomultiplier respectively.

8846-40, Session PMon

Investigations of acoustic wood for luthiers using terahertz imaging

Dominique Coquillat, Univ. Montpellier 2 (France) and Ctr. National de la Recherche Scientifique (France); Julien Moulin, Univ. Montpellier 2 (France); Jean-Paul Brouillet, Univ. Montpellier 2 (France) and Univ. Montpellier 1 (France); Nina V. Dyakonova, Frederic Teppe, Wojciech Knap, Univ. Montpellier 2 (France) and Ctr. National de la Recherche Scientifique (France)

New developments in terahertz technologies are opening the doors to sensing and imaging in industry. Terahertz imaging can be employed as a non-destructive evaluation tool of acoustic wood. Often difficult to detect visually, severe runout – that refers to the orientation of the wood cells not completely parallel to the board surface of a string instrument – can be detrimental to strength and sound vibrational characteristics. Most luthiers try then to avoid runout if possible. Terahertz imaging enables inspection not only for evidence of cracks, voids, defects, worm damage, but also for runout.

In the framework of the LABEX NUMEV project, terahertz imaging has been employed as a non-destructive evaluation tool of acoustic wood. The birefringence properties at terahertz frequencies associated with the fiber orientation are used to investigate wood runout.

Using Silicon MOSFET as sensitive, compact and cost-efficient terahertz detector, we have observed that there is a notable difference between the birefringence of the four acoustic wood species studied: western red cedar (Thuya plicata), spanish cedar (Cedrela odorata), indian rosewood (Dalbergia latifolia), and ebony (Diospyros sp), used for the sound board, the neck, the back and sides, and the fingerboard, respectively. Among them, the softwood red cedar has a strong anisotropy, whereas rosewood is very inhomogeneous spatially in density. The terahertz imaging in transmission mode measured as a function of both incidence and azimuthal angles, proposed here, can be relevant for luthiers to select acoustic wood without runout or to observe how wood has warped overtime.

8846-41, Session PMon

Polymer based single mode optical waveguide for spectroscopy applications

Maurine Malak, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Konstantins Jefimovs, EMPA (Switzerland); Hans Peter Herzig, Toralf Scharf, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Being low cost, light-weight, non-wearable, flexible and easily shaped, polymer materials acquired a high interest and became largely deployed in the microfabrication of passive optical devices. Oppositely to silicon, polymeric materials offer a transparency for light in the near infrared range.

For these reasons, we developed a compact 2-D low loss single mode optical waveguide fabricated with EPO materials. The waveguide geometry is of square shape, its refractive index distribution has a step-index profile and it is buried between two EPO-clad layers. Realized by polymer deposition, the guide consists mainly, of a stack of EPO-clad/EPO-core/EPO-clad layers sandwiched between two glass substrates having a thickness of 0.5 mm. The refractive index difference between the EPO-layers is 2.5x10-3. The waveguide dimensions are 3x2.2?m2. A cleaved single mode optical fiber, operating in the visible range (658 nm), is used to perform optical characterizations, double side polished structure exhibits an insertion loss of 2.6 dB, a numerical aperture of 0.25 and a cross-talk level of 15 dB for waveguides spaced apart by 150 ?m.

Intended for spectroscopy applications, the final demonstrator embeds a high reflectance mirror at the waveguide exit. Then, a standing wave interference pattern is build-up inside the optical waveguide. Sampling of the pattern using an array of nano-antennas deposited on top of the waveguide, yields information about the spatial distribution of the interferogram. Applying Fast Fourier Transform, the spectral content of the signal can be deduced and the prototype demonstrates a strong potential for applications of high performance spectroscopy.

8846-42, Session PMon

Transient mobility and photoconductive terahertz emission with GaP

Christopher M. Collier, Brandon Born, Xian Jin, Timothy M. Westgate, Max Bethune-Waddell, Mark H. Bergen, Jonathan F. Holzman, UBC Okanagan (Canada)

Wide-bandgap semiconductors are appealing materials for photonic systems seeking high electric field breakdown strengths, and photoconductive terahertz (THz) generation systems are a major example of this. Especially large THz powers can be achieved by biasing with high electric fields. Unfortunately, standard wide-bandgap semiconductors also have slow electron-hole recombination rates, and the corresponding nanosecond/microsecond carrier lifetimes can limit the THz system recovery. With this in mind, there is a concentrated effort to develop wide-bandgap semiconductors with ultrafast recovery rates. Such materials would provide high-power THz generation with picosecond recovery times.

In this work, GaP is investigated for use in photoconductive THz generation. The atypical bandstructure of GaP, with a central high-mobility Gamma valley being higher than the low-mobility L and X sidevalleys, is exploited to establish a transient state of high-mobility photoconduction. The subsequent scattering and relaxation of hot electrons into and within the lower-mobility sidevalleys leaves the material in a low-conduction state. Experimental and theoretical studies are carried out to show that this ultrafast transient mobility process, occurring over 800 fs, can create broadband THz pulses with reduced recovery times (and low leakage currents). The impacts of these findings are discussed for efficient and portable next-generation THz systems.

8846-43, Session PMon

Microstructure analysis of confined liquids with terahertz time-domain spectroscopy

Nicholas Y. Tan, Lynn F. Gladden, Axel Zeitler, Univ. of Cambridge (United Kingdom)

Due to the utility of porous materials as heterogeneous catalysts in chemical processes, the interactions between catalysts and the reactants at interfaces have been extensively studied with methods such as nuclear magnetic resonance (NMR) and electron paramagnetic resonance (EPR). Recent experimental work by Havenith et al. showed that terahertz time-domain spectroscopy (THz-TDS) was a useful tool in characterising adsorbed water in MOF-5. The authors found non-linear frequency dependent changes in the THz spectra, which was indicative of coupling between the lattice modes of MOF-5 and network motions of the bound water. Far-infrared spectroscopy has also been used to probe confined water in organic porous material. These measurements showed differences in the dynamics of water confined in small pores compared to water confined in large pores.

We present the terahertz absorption spectra of isopropanol and water confined in several porous catalysts: silicates, metal-organic frameworks and porous organic cages. The spectra are acquired using THz-TDS over the frequency range of 0.4 - 1.5 THz. The dielectric spectra are also presented, which cover both fast and slow liquid relaxation processes. These spectra are compared against bulk liquids to determine the effects of confinement.

The absorption spectra exhibit clear differences with varying levels of liquid loading. This is indicative of differences in the interfacial interactions between liquids and catalysts. In addition, significant differences were observed between the spectra of confined liquids and the bulk liquids, which clearly highlight the effect of confinement on the structuring of these liquids.

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8847-1, Session 1

Double pulse laser deposition of polymer nanocomposite: NaYF4:Tm3+,Yb3+ films for optical sensors and light emitting applications *(Invited Paper)*

Abdalla M. Darwish, Michael T. Sagapolutele, Simeon Wilson, Dillard Univ. (United States); Sergey S. Sarkisov Sr., SSS Optical Technologies, LLC (United States); L. Darayas N. Patel, Oakwood Univ. (United States)

The main objective of this paper is to demonstrate the feasibility of producing operationally Nanocomposite polymeric thin films for sensor and light emitting applications using the innovative modified double pulsed laser deposition (DPLD) technique. The existing PLD vacuum chamber was modified to accommodate multiple wavelength laser beams for in-situ-double-ablation/Deposition (DPLD) of multiple targets of host and dopants. Special design was made for cooling of the target to the threshold of the polymer ablation without interrupting the continuity of the ablation process. Multi-layered of nanocomposites of acrylic polymers and nanoparticles of NaYF4:Tm3+,Yb3+ are fabricated using ultra-violet (UV) radiation (355 nm) ablating polymer targets and near-infra-red (near-IR) radiation (1064 nm) ablating inorganic targets. The films were characterized using the reflected high energy electron diffraction (RHEED), XRD , XRF, AFM, and FTIR absorption spectroscopy and tested as possible chemical sensors and light emitters.

8847-2, Session 1

Improved SiPM device performance by introduction of a new manufacturing technology

Florian Wiest, Peter Iskra, Natsuki Miyakawa, KETEK GmbH (Germany); Thomas R. Ganka, Christoph Dietzinger, Univ. de Bundeswehr (Germany); Alicia Márquez Seco, KETEK GmbH (Germany)

Silicon photomultipliers (SiPMs) are intensely evaluated as a potential replacement of photomultiplier vacuum tubes for several applications. Essential key features are the photon detection efficiency, the dark count rate, the optical crosstalk and the scalability of the active area.

In order to achieve considerable improvements of these parameters, KETEK has introduced a new manufacturing technology based on 200 mm wafers and 0.35 µm stepper lithography. Important aspects of the well-established and for many years optimized KETEK Silicon Drift Detector technology could be transferred to the SiPM process.

Main items of the new technology are a narrow vertical trench around the individual microcells and an impurity getter: the first reduces the optical cross talk and the second the dark count rate by factor two, whereby the potential of this technology is still not maxed out.

A further aspect of the new technology is a low parasitic RC-value device concept: The reduction of parasitic RC-values is targeted on a scalability refinement of SiPM devices which is mandatory for active areas above 10 mm2.

Finally the geometrical fill factor and the light entrance window of the KETEK device has been further improved for which reason a 50 µm cell pitch device with a photon detection efficiency of 60% in the blue range will be presented.

Beyond that the SiPM devices show an extremely low temperature coefficient of the gain. This is due to an operation at very high overvoltage along with a low temperature coefficient of the break down voltage.

8847-3, Session 1

Colorless chalco-halide Ga2S3-GeS2-CsCl glasses as new optical material

Yannick Ledemi, Mohammed El Amraoui, Younes Messaddeq, Ctr. d'optique, photonique et laser (Canada)

Colorless sulfide glasses can be obtained by selecting appropriately the composition within the Ga2S3-GeS2-CsCl pseudo-ternary glass system. The addition of electronegative chlorine ions into the sulfide glassy network results in a widening of its optical bandgap without altering its infrared transparency. Glasses transparent from the near UV (380 nm) up to the middle infrared (11.5 ?m) are thus achievable. Such extended infrared transmission for a colorless glass is the widest among the known heavy metal oxide and fluoride glasses, e.g. fluoroindate glasses are transparent from 350 nm up to 8-9 ?m. We present in this work our recent progress on the preparation of this chloro-sulfide glass of high optical quality. Efforts have been devoted in a first step to reduce the content of extrinsic impurities such as OH, SH and H2O. In a second step, protective coatings have been deposited on polished glass samples to improve their chemical durability and assess their potential for practical applications. Large improvement of both optical quality, in terms of transmission spectrum flattening, and chemical durability were achieved. Finally, the high thermal stability against crystallization of this glass shows a high potential for lens molding and applications in multispectral imaging.

8847-4, Session 1

Fundamental studies on the correlation between antimony film properties and alkali-antimonide photocathode performance

Junqi Xie, Marcel Demarteau, Argonne National Lab. (United States); Henry J. Frisch, The Univ. of Chicago (United States); Edward A. May Jr., Robert Wagner, Jeffrey Williams, Argonne National Lab. (United States)

Photomultiplier tubes (PMTs), used as photodetectors, have many applications in fields such as medical diagnosis, chemical analysis, industrial measurement and scientific research. As an essential component of PMT, photocathode converts incoming photons into free electrons for output signal detection. The quality and performance of photocathode strongly determines the detection efficiency of a PMT. Currently, alkali antimonide compounds (Na-K-Cs-Sb) are the most widely used photocathode materials. Among most of the alkali antimonide photocathode deposition methods, an initial antimony (Sb) layer is required.

This talk will present the fundamental studies on the initial Sb film properties such as optical properties, thickness, structure and surface morphology. K-Cs-Sb bi-alkali photocathodes based on different Sb layers are deposited and the relation between overall quantum efficiency (QE) and Sb film properties are studied. Optimal Sb film thickness for high QE bi-alkali photocathode is concluded. These studies from the basis for further understanding of the key parameters affecting the cathode performance lead to the development of reliable high performance photocathodes with enhanced quantum efficiency, tunable cathode wavelength and time responses.

8847-5, Session 1

An analysis of the structural and optical properties of Eu doped gadolinium oxide (Gd2O3) planar waveguides fabricated by the sol-gel and dip coating methods

Matthew E. Edwards Sr., Quianna S. Johnson, Ashok K. Batra, Michael J. Curley, Alabama A&M Univ. (United States)

This study focused on the fabrication of Gadolinium Oxide (Gd2O3) and Gadolinium Oxide:Europium (Gd2O3:Eu3+) optical waveguides via the sol-gel and dip coating methods under atmospheric conditions. We have successfully established a method for the preparation and casting of the Gd2O3 sol via the dip coating method. Two different solvents, absolute ethanol and methanol, were used for the preparation of the optical waveguides. Their structural and resulting optical properties, in a waveguide configuration, were studied and compared. A new prism based coupling apparatus was built and used in this study to determine the efficiency of the fabricated waveguides. The optical behaviors and luminescence efficiency of the waveguides were examined according to doping concentration.

8847-6, Session 1

Organic octagonal quasicrystal mircocavity lasers based conjugated-polymer material with ultralow refractive-index

Xiao Chen, Guo-jian Yang, Fei-jun Song, Yi-quan Wang, Minzu Univ. of China (China)

We experimentally demonstrate and characterize an organic octagonal quasicrystal slab with a single-defect microcavity at low-index contrast. The gain medium is the conjugated-polymer, composed by two PPV derivatives, a BEHP-PPV and a MEH-PPV. By optical pumping, the lasing action is achieved at 607 nm with a FWHM of 1nm. The threshold of lasing is 9uJ/cm2. The intensity of the lasing peak depends linearly on the pump energy above the threshold.

8847-7, Session 1

The research on the photoemission of negative electron affinity GaN photocathode

Rongguo Fu, Nanjing Univ. of Science and Technology (China)

Aiming at the photoemission of p-GaN(0001) surface. Activation steps and evaluation of the NEA GaN photoelectriccathode is introduced. Cs and O were used for activation of GaN(0001) surface and the result were tested by using dedicated experimental system for activation and negative electron affinity photocathode. Some data,such as spectral response,quantum efficiency and the photocurrent during activation period etc. were got by the dedicated experimental system. The dipole layer formed on the surface of GaN after the activation with Cs/O is discussed, as the basis for calculating the escape probability of electron. The minority carrier diffusion length and the photoelectron escape depth were fitted by the theory equation,and the theoretical model of the photoemission were established. XPS surface analysis instruments were used for the surface photoelectron spectroscopy analysis before and after the activated GaN photocathode. The research combined with the intrinsic link between the state and the atomic percentage of the surface of Cs?O?Ga and N to determine the structure of the arrangement of surface atoms.Energy band theory were used for built the surface state of the theoretical model of negative electron affinity of GaN (0001) surface. Analysed the intrinsic relationship of negative electron affinity surface morphology ,spectral response , the minority carrier diffusion length, minority carrier lifetime and other parameters. Studied the effect of the mechanism of surface state on photoemission. In order to get high quantum efficiency of the vacuum type ultraviolet detector ,and theoretical basis of NEA photocathode.

8847-8, Session 1

Optical properties of (1-x)Pb(Zn1/3Nb2/3)O3-xPbTiO3 single crystals

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Optical properties of (1-x)Pb(Zn1/3Nb2/3)O3-xPbTiO3 (PZN-xPT, x=5%, 9% and 12%) single crystals have been comprehensively investigated. The PZN-xPT single crystals used in this study were grown using a high temperature flux method. Refractive indices (nij) were measured by the Brewster's angles (?B=tan-1n) at different wavelengths. Dispersion equations of refractive indices were obtained. After poled along [001] direction, the transmittance of PZN–12%PT single crystal is more than 65% from 0.5 to 5.8 ?m, which is much higher than that of PZN–5%PT and PZN–8%PT single crystals. PZN–12%PT has a tetragonal phase, its spontaneous polarization PS is along [001] direction. After poling, it could form a single domain structure. Orientation and temperature dependences of the electro-optic coefficient were investigated at He-Ne laser by the Senarmont compensator method. Large effective electro-optic coefficient (?c = 430 pm/V) was observed in [001]-poled PZN-0.09PT crystal. More importantly, ?c of tetragonal PZN-0.12PT is about 130 pm/V, which is almost unchanged in a temperature range -20~80 °C. The ?c of PZN-xPT single crystals are much higher than that of widely used electro-optic crystal LiNbO3 (?c = 20 pm/V). They can be comparable with transparent ferroelectric ceramics PLZT 12/40/60 (140 pm/V). These excellent optical properties make the PZN-xPT single crystals promising candidates for electro-optic modulation applications.

8847-10, Session 2

Enhanced gain dynamics in photorefractive polymers *(Invited Paper)*

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Photorefractive polymers have been extensively studied for over two decades and have found applications in holographic displays and optical image processing. The complexity of these materials arises from multiple charge contributions assisting in the formation of competing photorefractive gratings. Analysis of the time dynamics of the two-beam coupling signal is a convenient way to extract the information about the charge species responsible for the grating formation in photorefractive polymers. It has been recently shown that in a photorefractive polymer at relatively moderate applied electric fields, the primary charge carriers (holes) establish an initial grating, followed by a subsequent grating (electrons). This secondary grating competes with the primary grating and decreases the two-beam coupling efficiency. In this paper, it is shown that with relatively large applied electric fields, the steady-state two beam coupling efficiency is enhanced. Our conclusions are supported by experimental two-beam coupling results in a reflection geometry using two different wavelengths (532 nm and 633 nm) and different illumination and biasing conditions.

8847-11, Session 2

Contribution of diffusion and photovoltaic effect to self-pumped reflection gratings in photorefractive lithium niobate

Rola Aylo, Univ. of Dayton (United States) and The Catholic Univ. of America (United States); Partha P. Banerjee, Univ. of Dayton (United States); Sergei A. Basun, Air Force Research Lab. (United States) and Azimuth Corp. (United States); Dean R. Evans, Air Force Research Lab. (United States)

Self-pumped reflection gratings have been extensively studied in various photorefractive materials. In photorefractive lithium niobate, diffusion and photovoltaic effects contribute to grating formation, with the latter being responsible for non-ideal phase difference between the intensity and induced refractive index gratings. The participating optical fields responsible for the intensity and index gratings have to further obey the EM boundary conditions at the interfaces, which are critical in a self-pumped reflection grating geometry.

The transfer matrix method (TMM) is a convenient and rigorous matrix based approach for optical field simulations which takes into account multiple reflections in layered media and all EM boundary conditions. The longitudinal refractive index modulation along the propagation direction is therefore treated as a multilayer system and TMM is applied to analyze two-wave coupling due to self-induced reflection gratings in photorefractive lithium niobate. A simple model for the induced nonlinear refractive index due to diffusion and photovoltaic effects, based on material parameters, is adopted. Since the refractive index is induced, computations are performed iteratively until numerical convergence is achieved. The exact refractive index profile (and optical field distribution) inside the material is computed for the self-pumped reflection grating geometry, along with the overall transmission and reflection, and for both orientations of the c-axis. Numerical simulations are compared with experimental results.

8847-12, Session 2

Lens array plate reference modulation in collinear volume holographic storage system *(Invited Paper)*

Yeh-Wei Yu, Chih-Yuan Cheng, Ching-Cherng Sun, National Central Univ. (Taiwan)

In this era of information proliferation, the demand of huge data storage keeps increasing. Library-style tape storage systems have been used for archive. However, the serial access of this method makes it too inefficient for modern applications. Volume holography storage (VHS) system which owns high access rate, high transfer rate and high storage capacity becomes the best modern solution. Among all the existing VHS techniques, collinear VHS system is treaded as the best candidate for commercial market because of its simplicity and compactness. Unfortunately, the transfer rate is limited by the current technique of reading devices and is slower than the mature tape technique.

The lens array plate (LAP) reference modulation can improve the signal-to-noise ratios (SNR) of collinear VHS 10 times better than current techniques, because the point spread function of colliner system is autocorrelation of reference modulation and the autocorrelation of LAP is very sharp. In this paper, we analyze shift selectivity of LAP and intensity distribution inside the disk of LAP. We also show the transfer rate of collinear system can be improved to compete with the tape technique after optimization of LAP.

8847-13, Session 2

Theoretical model of multilayer collinear volume holographic storage *(Invited Paper)*

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Collinear holographic data storage (CHDS) is a promising technology for the commercialization of the volume holographic data storage because it is compact and it can provides high data density and high data transfer rate simultaneously[1]. In order to achieve higher data storage density of the CHDS, multilayer recording with a coaxial transmission-type configuration was developed to make full use of the medium dynamic range along the normal direction (z-axis)[2]. Recently, a new multilayer collinear holographic memory with a movable random phase mask (MRPM) has been proposed to reduce the interlayer crosstalk experimentally[3]. The theory of multilayer collinear holographic data storage (MCHDS) is in great need to characterize this method. In this paper, the expression of the stationary holographic fringe in the recording material is presented. The influences of the NA of the object lens and the pattern of the reference beam on the size of the holographic fringe are discussed. Then a theoretical model is applied to calculate the field distribution of the reconstructed light on the surface of the detector by considering the volume recording material as many thin slices. Through calculating the field distribution of the reconstructed image, we sum up the relationship between the size of the holographic fringe in the recording material and the reconstructed pattern. By this method, we could discover why the signal to noise ratio and medium dynamic range consumption are enhanced when the MRPM is applied theoretically.

8847-14, Session 2

History of Kukhtarev's equations and their legacy: band transport model revisited *(Invited Paper)*

Sergei F. Lyuksyutov, The Univ. of Akron (United States)

The author had closely witnessed and monitored progress of Dr. Kukhtarev's ideas and experimental verification of his ideas in the Institute of Physics in Kiev, USSR in the 80s. The renaissance of the photorefractive effect is routinely associated with the paper published in Kukhtarev, Markov, Odoulov, Soskin and Vinetskii "Holographic storage in electrooptic crystals, Ferroelecrics, 22, 949-60 (1979). Although the co-authors of this paper may have different interpretations on the weight of personal contributions, I shall present my, independent, view. There is a consensus of opinion that Kiev group provided the best foundation for the future theoretical and experimental work in the area of photorefraction. There have been plenty of outcomes of Dr. Kukhtarev contributions in the past 40 years: Phase conjugation in photorefractive media, self-oscillation, gain enhancement by detuning, photo-galvanic current, space charge waves, the list will go on and on... This presentation is to tribute Dr. Kukhtarev various contributions in the area of photorefraction.

8847-15, Session 2

Compact crystal accelerator-undulator based on fringing electric-field holographic super lattice *(Invited Paper)*

Nickolai V. Kukhtarev, Tatiana V. Kukhtareva, Alabama A&M Univ. (United States)

We describe modeling of compact crystal electron beam accelerator-undulator, based on the fringing electric field, holographically recorded in the photorefractive crystals. Recently, we have demonstrated that compact pyro electric/photogalvanic crystal accelerator may produce focused electron beam with energies of electrons up to 150

KeV. Focusing structure depends on the crystal geometry and allows producing cylindrical or plain-sheet focused beams. In this paper, we propose combination of compact crystal accelerator with crystal-based electrostatic undulator. In suggested device, the plain sheet electron beam from the compact crystal accelerator is focused into plain wave-guide composed of two crystals. One crystal serves as an additional electrostatic accelerator, another crystal contains build-in electric-field superlattice. The holographically recorded electric field superlattice is serving as a compact electrostatic ondulator, replacing bulky magnetic ondulator used in the traditional free-electron coherent amplifiers and lasers. The theoretical modeling shows that recommended undulator structure might act as an efficient amplifier for a seeding electromagnetic radiation in a microwave and in THz regions. An energy supply for this device may be cheap heat source (in pyroelectric mode of operation) and/or incoherent light source (including sunlight, for photogalvanic mode of operation).

8847-16, Session 2

Laser-induced 2D periodic structures of charged particles concentration in semiconductor under the condition of optical bistability existence

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We analyze the laser-induced 2D periodic structure in semiconductor under the condition of the optical bistability existence. Optical bistability appears due to nonlinear dependence of semiconductor absorption coefficient of charged particles concentration because of both the Fermi energy level renormalization and the Burstein-Moss effect. The electron mobility, diffusion of electrons and laser-induced electric field are taken into account at analyzing of laser pulse propagation in the semiconductor.

We found out various modes of laser-induced spatial structure developing on charged particles concentrations in dependence of optical intensity and absorption coefficient. One of them consists in periodic appearance and moving of stable spatial electrons distribution.

8847-17, Session 2

All-normal dispersion photonic crystal fiber for parabolic pulses and supercontinuum generation

Igor A. Sukhoivanov, José Amparo Andrade Lucio, Oleksiy V. Shulika, Univ. de Guanajuato (Mexico); Sergii O. Iakushev, Kharkov National Univ. of Radio Electronics (Ukraine); Alejandro Barrientos García, Univ. de Guanajuato (Mexico); Gabriel Ramos-Ortiz, Ctr. de Investigaciones en Óptica, A.C. (Mexico); Igor V. Guryev, Oscar G. Ibarra Manzano, Arturo Garcia Perez, Univ. de Guanajuato (Mexico)

Supercontinuum (SC) generation is a very active field of research during the last decade. Recently it was shown that all-normal dispersion photonic crystal fibers (ANDi PCFs), which exhibit convex dispersion profiles flattened near the pump wavelength are able to provide highly coherent, flat-top and octave-spanning SC. Here we have designed ANDi PCF with a flat top located at 800 nm. We investigate its applicability for SC generation and parabolic pulse formation with conventional Ti:Sapphire lasers. At the first step we have designed ANDi PCF suitable for SC generation and parabolic pulse formation beyond optical wave breaking. We consider here PCFs with solid core and triangular lattice of air holes. Parabolic pulse formation and supercontinuum generation in this fiber is analyzed both in time and frequency domains by solving GNLSE. It was shown that under pumping within the short wavelength range about 10 nm around the zero-third-order-dispersion wavelength the SC generation is stable under pumping by pulses up to 35 nJ, i.e. does not demonstarate any signatures of breaking neither in time nor frequency domains.

8847-18, Session 3

Side illuminated optical fiber as a multiplexing element for spectroscopic systems *(Invited Paper)*

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A new type of colorimeter was demonstrated using a side illuminated optical fiber. This configuration is simple, low cost, does not require a sensitive coating and can analyze multiple samples placed at different positions along the fiber. By side illuminating different spots of the cylindrical surface of the fiber, with multiple light sources, it is possible to guide different signals in a single waveguide resulting in a multiplexed device. In addition to that, this system requires a single detection system that further lowers the cost of analyzing multiple samples.

This proof of concept used a tapered plastic fiber, a support for three LEDs, an inexpensive photo diode, a read-out and food dye solutions of different concentrations. The solutions were placed in different cuvettes along the fiber length and illuminated by the LEDs. Light from the source passes through the solution, strikes the side of the fiber and is guided to the detection system. The measured light intensity and spectral distribution depend on the color and/or darkness of the sample.

Several calibration curves were obtained using different light intensities and detector configurations. It was found that by increasing the light intensity, the sensor sensitivity also increases. It was also found that by making small modifications of the detection system, the colorimeter's dynamic range can also be controlled. By combining these two capabilities we were able to examine distinct dynamic range regions at different sensitivity levels.

With these successful demonstration, this device is now being modified to make fluorescence and scattering measurements.

8847-19, Session 3

Frequency doubled high-power semiconductor disk lasers for stereo projection and ion traps

Alexander Hein, Susanne Menzel, Andreas Ziegler, Rudolf Roesch, Peter Unger, Univ. Ulm (Germany)

We present high-power optically pumped semiconductor disk lasers (OPSDLs) emitting in the 900-1100 nm band which are intra-cavity frequency doubled to access the visible spectrum at blue and green wavelengths. The emission at wavelengths around 450-470 and 520-540 nm yield highly advantageous gamuts for display applications, and can be further utilized for stereo projection. Moreover, certain wavelengths of the converted radiation, e.g. 493.2 nm and the inherent good beam quality of these lasers can be used in optical trapping experiments for ions, inaccessible by other laser types. We focus on presenting the design, fabrication, and characteristics of these devices. In particular, the design of the semiconductor layer structure, the epitaxial growth, device mounting and processing, as well as the thermal management strategy are considered, aiming to produce high optical outputs in the fundamental regime. Preliminary measurements such as photoluminescence and reflectivity spectra are introduced as device assessment tools from which basic characteristics, e.g. the dominant micro-cavity resonance, and expected wavelength and temperature behavior can be derived. During laser operation fundamental output

powers exceeding 20 W, and blue and green radiation with output powers of 5-10 W were achieved with single-chip devices, and operating temperatures of 90°C with watt-level IR outputs were possible. The IR and visible outputs show optical-to-optical conversion efficiencies above 40% and 20%, respectively. Furthermore, broad wavelength tuning ranges of more than 20 nm (513-535 nm) in the second-harmonic regime could be realized.

8847-20, Session 3

Design of the optical concentrator using holographic techniques for solar cells

Wei-Hung Su, Wei-Ting Chen, National Sun Yat-Sen Univ. (Taiwan)

An approach using holographic techniques to fabricate an optical concentrator for a thin film solar cell is described. This concentrator consists of a hologram and a lenticular lens. The lenticular lens collects the sunlights from arbitrary incident angles. The sunlights are then launched into the hologram and generate diffracted light waves. Most of the diffracted waves are normally incident into the solar cell. Thus, reflectivity of the light on the surface of the solar cell is minimized, and the solar energy concentration is increased.

8847-21, Session 3

Broadband large field of view electro-optic modulators using potassium tantalate niobate (KTN) crystals

Yun-Ching Chang, Shizhuo Yin, The Pennsylvania State Univ. (United States); Robert C. Hoffman, Andrew G. Mott, U.S. Army Research Lab. (United States)

It is well known that potassium tantalate niobate [KTa1-xNbxO3 (KTN)] crystals have a large quadratic electro-optic (EO) coefficient. However, high quality, sizable KTN crystals suitable for device fabrication have only become commercially available in the past several years. By taking advantage of the recent advances in KTN crystal growth, a broadband large field of view (FOV) EO modulator is developed and presented in this paper. The experimental and theoretical studies indicate that the built EO modulator not only has a broad bandwidth (~ 1 GHz) but also has a large FOV (+/- 30 deg) because cubic phase KTN crystals do not introduce any intrinsic birefringence without applying the external electric field. Furthermore, unlike waveguide-based EO modulators that have a very small (a few microns) cross section with a multi-gigahertz bandwidth, the EO modulator presented in this paper has a larger (from millimeter to centimeter range) cross-section. The result is a core enabling device for several practical applications such as modulating retro reflector (MRR) for broadband free space optical communications. Finally, the modulation bandwidth can be further enhanced by taking advantage the broad transmission band (400 nm - 4000 nm) of KTN crystals (e.g., using WDM).

8847-22, Session 3

Novel design of a highly sensitive micro-displacement sensor based on photonic crystal waveguides

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A novel ultra-sensitive design of micro-displacement sensor, useful for integration with MEMS, consisting of fixed and movable PCWGs is presented. The sensor design consists of the PC of hexagonal array and creation of angular intersection of a PCWG (of width 5.52 µm) with the common axis of the fixed (connected to a stationary substrate) and movable PCWGs. The 2-D hexagonal arrangement (a=2.76µm) of air holes (r=1.1µm) drilled in Silicon, is taken into consideration because of its practical reliability and fabrication. The band diagram of the structure is numerically simulated using Plane Wave Expansion (PWE) method and it is found that the TM mode of wavelength 9.02µm appears in the midst of the Band-Gap region. The operation of the device with the working wavelength of 9.02µm emitted from a Co2 laser with a view of its industrial applications.

Numerical simulations with the magnitude of angular displacement of moving PCWG increasing by 0.2µm at each step of simulation have been performed. Sensing is performed by analyzing the energy distribution among the PCWGs and by detecting the variation of Difference in normalized-Power (DIP) exiting the waveguides.

The sensitivity of the proposed novel design is much better than the existing literature's results. The sensitivity of the proposed design is also compared with photonic crystal structure in square lattice in silicon and also with silicon rods assembled with hexagonal lattice with a view of its applications in photonic crystal based MEMS.

8847-23, Session 3

Full-wave FDTD analysis of nonlinear photonic crystal fibers

Igor V. Guryev, Igor A. Sukhoivanov, José Amparo Andrade Lucio, Everardo Vargas Rodriguez, David Claudio Gonzalez, Ruth Ivonne Mata Chavez, Oleksiy V. Shulika, Univ. de Guanajuato (Mexico)

Nowadays, technology allows creating photonic crystal fibers with almost any imaginable refractive index profile which leads to a variety of applications. Therefore, at the design stage it is important to be able to predict and optimize their characteristic. Existing FDTD-based methods allow treating for the material dispersion. However, in case of femtosecond pulses propagation or high-power CW lasers the waveguide dispersion is changed due to optical nonlinearity. Another important drawback of the existing methods is using the square unit cell of the fiber. This assumption allows quite easy implementation of the Leap-Frog algorithm and is acceptable for eigen-frequency computation and modes analysis. However, it introduces an error into the waveguide dispersion value.

In this work we have developed, implemented and optimized the full-vectorial FDTD-ADE method for precise investigation of dispersion characteristics of nonlinear photonic crystal fibers. The method takes into account hexagonal shape of the fiber unit cell, material dispersion of the refractive index and the nonlinear effects. In case of low intensity (linear case), the dispersion have been compared with the one obtained by the full-vectorial finite elements method which is proved to be precise and stable. In case of high radiation intensity (nonlinear case) the FDTD-ADE method has shown good results in the works published by Allen Taflove.

The method is implemented using advanced computing technologies such as parallel computing and GPU computing and is tested on the supercomputer "Piritakua" of the University of Guanajuato. High performance of the method allows using it in the optimization algorithms.

8847-24, Session 3

Phase-shift formed in a tapered long period fiber grating and its application to simultaneous measurements of temperature and refractive-index *(Invited Paper)*

Hongpu Li, Keisuke Hishiki, Shizuoka Univ. (Japan)

In the past few decades, the studies on the phase-shifted long-period fiber grating (LPG) have attracted increasingly interest attributed to its unique properties, such as the narrow resonant bandwidth, high sensitivity to the environmental parameters which makes it the ideal role being utilized as the all-fiber-type biochemical sensor, optical switching, and all-optical processing elements. To date, various methods have been developed to fabricate the phase-shift LPGs. However, until present, the quantitative analyses on the calibration of the resulted phase-shift and the relationship between the transmission characteristics (wavelength of the loss peak and the loss depth) and the amount of the phase-shift have rarely been investigated, which is, however, very important and strongly demanded for its practical application to either the all-optical signal processing or as a high-sensitive fiber devices for measuring the environmental parameters, such as the temperature, strain, transverse load, pressure, and refractive index-change of the surrounding materials. In this paper, a novel approach to calibrate a phase-shift formed in a LPG is proposed and successfully demonstrated, which is based on the use of either a power- or a wavelength-interrogation technique to the loss-peak existed in the transmission spectrum of the phase-shifted LPG. Moreover, in this study, by tapering a LPG with CO2 laser, phase-shift is successfully created at central part of the LPG. Finally, base on the use of this kind of phase-shifted LPG, a simultaneous measurement for the temperature and the surrounding refractive index has been proposed and experimentally demonstrated.

8847-25, Session 3

Intra-cavity index sensor based on ytterbium-doped photonic crystal fiber

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Photonic crystal fiber with air holes in the cladding region has attracted high attention in the development of new all-fiber sensor due to its many peculiar properties, just like the endless single-mode characteristic, controllable dispersion, etc. In this paper, we propose an intra-cavity index sensor based on double cladding ytterbium-doped photonic crystal fiber filled with liquid analyte in the air holes of optical fiber cladding. The proposed Yb3+-doped photonic crystal fiber consists of two claddings and an Yb3+-doped core and the internal claddings consists of three layer air holes. In such sensor, when pumped by 976 nm light, the output power of the ytterbium-doped photonic crystal fiber laser at 1060nm can be influenced obviously by a bit change of the refraction index of liquid analyte in the air holes of optical fiber cladding to achieve the intra-cavity fiber sensing. We have got the relationship between effective refractive index of analyte and the confinement loss, output power of intra-cavity index sensor and cavity loss coefficient, output power and the end reflectivity by finite element method, respectively. The numerical analysis shows that the power change is larger in a small range of loss when the end reflectivity is higher, and the sensor's sensitivity will be higher for the change of refractive index of analyte. The intra-cavity photonic crystal fiber sensing system has great practical value and significance for their advantages of compact structure and high sensitivity.

8847-26, Session 3

Piezoelectric resonance calorimetry of nonlinear-optical crystals under laser irradiation

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Conventional method for the precise determination of optical absorption coefficients of nonlinear-optical crystals is laser calorimetry. It is based on measurements of the heating kinetics of air near the crystal surface during and after laser irradiation. Both optical absorption and heat transfer coefficients are then calculated by solving nonstationary heat conduction equation taking into account boundary conditions. Novel modification of calorimetry technique that we propose is to use concept of the crystal equivalent temperature (?eq) for measuring temperature kinetics of laser heated nonlinear-optical crystal. Piezoelectric resonances are observed in radiofrequency spectra of the crystal response to the applied probe electric field. Preliminary calibration of resonance frequency Rf dependence on temperature is performed during uniform crystal heating. So each Rf value corresponds to the certain crystal temperature T and Rf linearly depends on temperature with piezoelectric resonance thermal coefficient Kprt. Then crystal's ?eq kinetics is directly measured using resonance frequency shift ?Rf dependence on time when the laser power is switched on. Characteristic time constant ? of crystal ?eq kinetics during laser heating is determined using exponential fitting: Rf(t)=[Rf(0)–Rf(P)]exp(–t/?)+Rf(P), where Rf(P) is stationary value corresponding to laser power P. Equivalent temperature stationary value is ?eq(P)=T0+?Rf(P)/Kprt, where T0 is crystal temperature at P=0. This approach allows to measure precisely nonlinear-optical crystal true temperature kinetics during its laser heating and to determine both heat transfer and optical absorption coefficients using nonstationary heat conduction equation. Both coefficients were measured for LBO and PPLN crystals using CW Yb-doped fiber laser (1064 nm).

8847-27, Session 3

The path forward: silicon optical modulator for CMOS ICs

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It is widely known that a reverse-biased p-n junction under avalanche breakdown has the ability to emit visible light. This paper reviews a silicon p-type metal-oxide-field-effect-transistor (Si-PMOSFET) device that can work as two gate-controlled diodes symmetrically connected in parallel. More specifically, the "P+ type Drain/Source" terminal is connected to the ground and the "N type substrate" terminal operates at a positive voltage that is a fixed value, thus the variation of the voltage of the insulated-gate terminal can adjust the field distribution at the depletion region of the "P+ type Drain/Source"-"N type substrate" reverse-biased junction. Due to the correlation of the breakdown current flowing through the p-n junction and the optical emission power from the avalanching region of the p-n junction as a function of the filed distribution, the optical intensity seems to be reasonably feasible by means of the varying the gate voltage. It is noted that, compared with the Si-diode LED, a major advantage of the Si-PMOSFET LED is that this device is a three-terminal device which has a gate terminal. Moreover, because of the full compatibility with the standard silicon complementary-metal-oxide-semiconductor (CMOS) process, this Si-PMOSFET LED is capable of integrating with other silicon devices or circuits very well to realize monolithically optoelectronic integration.

8847-28, Session 4

Active gating as a method to inhibit the crosstalk of single photon avalanche diodes in a shared well *(Invited Paper)*

Anna Vilà, Eva Vilella, Oscar Alonso, Andreu Montiel, Angel Dieguez, Univ. de Barcelona (Spain)

Recent advances in Single Photon Avalanche Diode (SPAD) arrays have been proposed to improve the fill factor, by confining several SPADs in the same macropixel sharing the well. The main issue of this approximation relates to the ease of crosstalk, as the charge generated by the avalanche in a pixel can easily arrive through the substrate until the neighbouring ones. This crosstalk grows with the signal, and consequently can represent a non-negligible noise in the receiving pixel. In significant applications of SPAD arrays in which the measurement is triggered only in short and well-defined time periods that are known in advance, such as 2D and 3D vision systems of fluorescence lifetime imaging microscopy, the pixels can be inhibited before the arrival of the crosstalk charge.

To evaluate the effectiveness of this approximation, this paper reports the crosstalk characterization in an array of five SPADs fabricated in conventional 0.35um HV-CMOS technology in the same n-well, giving a fill factor of 67%. Measuring with a long gating time a crosstalk not less than 5% is observed. However, reducing the gating time below 4ns completely eliminates the crosstalk, as predicted by the theory and by TCAD simulations. The technique has shown to provide good spatial resolution and contrast in 2D imaging with the proposed SPAD technology.

8847-29, Session 4

Fabrication of nanostructures on curved surfaces

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In this paper, the fabrication of nanostructures in curved surfaces is presented, including the used materials, the fabrication methods, and the experimental results. The potential civilian applications such as broadband anti-reflection coating for optical lenses are also discussed.

8847-30, Session 4

Torsion sensor using a Mach-Zehnder interferometer

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In this paper, a novel torsion sensor base on a Mach-Zehnder interferometer is presented. The interferometer is achieved by fusion splice an Ytterbium doped photonic crystal fiber (YbDPCF) of double cladding between two single mode fibers (SMF). When a single mode fiber and an YbDPCF are fusion splice, a collapse of air holes take place, thereby the fundamental mode of the SMF enters into YbDPCF to cause core and cladding modes excitation. Hence a modal interference technique is achieved using this interferometer. This technique is induced because the cladding of the YbDPCF has an effective refractive index smaller than the core index therefore a phase difference between cladding and core is produced. This phase difference generates two optical paths and consequently some modes are propagating both the core and cladding. Then, the YbDPCF is fusion splice with another single mode fiber obtaining a SMF-YbDPCF-SMF structure. An image of the modes propagation inside of the YbDPCF was achieved. This image was obtained using an optical beam profile. The torsion sensitivity obtained is 0.05nm/° in torsion range from 0° to 360° along with a sensitivity of 0.06 dBm at a specific wavelength. Finally the interference fringes and torsion characteristics have been experimental investigated and demonstrated. This compact fiber component with acceptable sensing performance makes it a good candidate for the measurement of numerous physical parameters.

8847-31, Session 4

Band-stop filter at microwave frequencies using metallic photonic bandgap structures

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In this paper design and fabrication of a wide band One-Dimensional Photonic Bandgap Structures (PBS) which leads to Band Stop Filter (BSF) at 12 GHz is presented. Design and fabrication of One-Dimensional PBG-BSF is carried out and the effect of variation in period of the lattice and defect on propagation characteristics of 1-D PBG-BSF is studied. Firstly the eight slot periodic structures in one dimension are created on very thin metallic sheet and then by breaking the periodicity of the structure, a defect state is created in the PBG structures. The defects thus created leads to isolated energy levels within the energy gap. Defects may permit localized modes to exist with frequencies inside the PBG. Some of the measured results have been verified with the modeling results using MoM based IE3D software. In particular for the frequency range 6 GHz to 13.5 GHz, with a wide band gap centered at 12 GHz has been observed with the performed experiments for eight slot one dimensional PBG structure and this has band width of 1 GHz (approximately) agreeing well with the simulated results. Various other one Dimensional PBG periodic structures and structures with defect is fabricated and transmission parameter is observed which agrees well with the simulated results. Detail fabrication parameters and methods will be presented at length in the full paper.

8847-32, Session 4

Dynamic characteristics and optimization of optical power limiter based on Kerr saturable nonlinear photonic crystal

Juan R. Cabrera Esteves, Igor V. Guryev, José Amparo Andrade Lucio, Igor A. Sukhoivanov, Everardo Vargas Rodriguez, Univ. de Guanajuato (Mexico)

New advances on recent Pulsed and CW high power lasers are being widely used on optical communication. The compact and effective optical limiters have more important than ever. The aim of this work is to investigate the dynamic characteristics of a structure of photonic crystal with a nonlinear element as well as to optimize the parameters of the structure to create an optical limiter suited both for CW and pulsed radiation. The finite-differences time-domain (FDTD) method extended by the auxiliary differential equation (ADE) was applied to obtain the intensity-dependent spectra data of the structure for both CW and pulsed radiation. With data obtained, we generated graphics for both transmission spectrum and transmission characteristics at different intensities. According with graphics, the optical limiting was observed within wide wavelengths range for both CW and pulsed radiation. Therefore, due to scalability properties of PhC, the required limiting can be achieved by proper geometry selection. In spite of the lots of advantages such as compactness, integrability and tuneability, the investigated structure has significant disadvantages to be worked on. The most important one is the dependence of the characteristics on the pulse duration. This happens because of the high-Q resonator formed by the PhC with defect. However, with further optimization this disadvantage can be entirely eliminated.

8847-33, Session 4

Design of photonic crystal architecture for optical logic and gates

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In this paper, we report the designs of optical logic AND gates in Y shaped photonic crystal waveguides based on two structures, one of which is a hexagonal lattice with silicon rods in air (SRA) and another is the hexagonal lattice arrangement of air holes in silicon (AHS). In both the structures an air waveguide with two input ports and one output port has been created and a rod in one design and a hole in another design have been introduced at the center of the Y shaped waveguide. After the optimization, the radius (rc) and interaction length (L) of the central rod for rod structure has been taken as rc =0.05a and L=0.1a, respectively,

where 'a' is the lattice constant. For AHS structure, the radius of central hole in the Y shaped air waveguide has been optimized as rc =0.25a. After the optimization, the proposed structures have been verified to work as AND gates using the FDTD method. For input launch at the single input port, output power for SRA and AHS structures have been obtained as 0.328P0 and 0.406P0, where P0 is the input power. Similarly for input launch at both the input ports, output power obtained for SRA and AHS structures are 1.310P0 and 1.624P0. It has been analyzed that the bit rate for SRA structure is 2.016Tbit/s and for the AHS structure is 1.785Tbit/s. Thus, the proposed photonic crystal structures could really work as an efficient AND optical logic gates.

8847-34, Session 4

Tiering effect of solid-core photonic crystal fiber on controlled coupling into multimode fiber

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Premise backbones, primarily multimode fiber (MMF), are reaching their fundamental capacity limits due to rapidly increasing bandwidth demands driven by the advent of multimedia-rich data services. Current techniques for advancing the capacity limit of MMF include controlled coupling, electronic dispersion compensation (EDC), offset launch, wavelength division multiplexing and orthogonal frequency division multiplexing. Controlled coupling into a MMF by contriving the launch beam to substantially fit an eigenfunction of the MMF waveguide have been achieved using spatial light modulators (SLMs), single mode fibers (SMF), phase masks and gratings. Controlled coupling improves the channel impulse response of the MMF by suppressing undesirable modes, converting modes or equalizing the arrival times of propagating modes. Solid-core photonic crystal fibers (SC-PCFs) offer an attractive alternative for increasing the transmission capacity of MMF via controlled coupling. This paper explores the potential of SC-PCF for controlled coupling into a MMF. Several structural designs of solid-core PCF waveguides are explored. The power coupling performance is evaluated in terms of the power coupling efficiency from the SC-PCF into the MMF, distortion of the spatial transverse modal field at the MMF and bit-error rate. It is shown that the power coupling from the PCF to the MMF may be controlled by the diameter of the air holes, the distance between two holes and the ratio of the distance between the holes and the size of the hole. The power coupling performance is investigated at three wavelengths - 850nm, 1300nm and 1550nm.

8847-35, Session 4

Optimization of maximum power transfer in outer waveguides by properly designing the inner waveguide and using modified coupled mode analysis for graded index multi-waveguide systems

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We present the modified scalar coupled mode analysis for the N-waveguide diffused channel waveguide directional power coupler. The study simulates the lateral evanescent field coupling in Graded Index Multi-Waveguide Systems. In a two-step procedure, the propagation characteristics of individual waveguides have been obtained first using the completely analytical variational approach. Consequent upon obtaining the individual waveguide characteristics, the complete scalar coupled mode theory has been developed to obtain the supermodes corresponding to the coupled waveguide configuration. The fabrication technique of the inner waveguide for maximum power transfer between the outer waveguides is optimized properly.

8847-36, Session 4

Ultrafast transient characteristics of photoconductive elements for optical wireless communications

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Semiconductor switches are important photoconductive (PC) devices for modern optoelectronic communication systems. Advancements in these PC devices have focused mainly on optical fibre implementations—with material and structural developments establishing ultrafast optoelectronic switching times. The use of PC devices becomes complex, however, when these elements are applied to emerging optical wireless communications (OWC) systems as visible light links. Indoor visible light OWC systems are typically deployed with distributed optical lighting/transmitter grids, so mobile PC devices must offer multidirectional and broadband capabilities (along with the aforementioned capability for ultrafast optoelectronic switching times). Integration of all these OWC capabilities can be challenging.

In this work, an integrated PC sensor is studied for use in visible light OWC links. The sensor applies the standard PC switch, being a biased metal-semiconductor-metal gap, in a three-fold-symmetric corner-cube architecture with a summed output photocurrent at the vertex. Such a form facilitates bidirectional retroreflective communications while meeting the OWC requirements for multidirectional and broadband capabilities. The ultimate capability for ultrafast optoelectronic switching times must be carefully considered, however. The 3-D form that allows for multidirectionality also introduces an internal transit time response, while the visible light photoexcitation that allows for broadband operation also introduces a complex transient material response. These transit time and material responses are analyzed in this work for the integrated PC sensor. It is shown that the responses can be carefully balanced for ultrafast (picosecond) optoelectronic switching times. Such a device can become an important element for emerging visible light OWC systems.

8847-37, Session 4

Equivalent temperature of nonuniformly heated nonlinear-optical crystals in course of laser radiation frequency conversion

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Precise temperature control of the nonlinear-optical crystals plays crucial role in various laser frequency conversion processes. Piezoelectirc resonance spectroscopy technique gives opportunity to measure the crystal temperature during its linear and nonlinear interaction with laser radiation. This method is based on the registration of the crystal piezoelectric resonance frequency Rf change caused by the interaction of the laser radiation with crystal. Piezoelectric resonance can be observed by measuring the response of crystal sample to the applied external electric field. Electric field of the varying radiofrequency affects the nonlinear-optical crystal (PPLN), which is placed in unclamped manner between two strip electrodes and is connected in series with the load resistor. For each value of the electric field frequency the amplitude and the phase of the voltage on the resistor are measured by the lock-in amplifier. Preliminary calibration of resonance frequency dependence on temperature T is performed during uniform crystal heating. Here Rf linearly depends on temperature with coefficient Kprt. It is shown that nonuniform crystal heating by laser radiation can be characterized by equivalent temperature ?eq. At certain pump power P the crystal equivalent temperature is directly determined from measured Rf shift: ?eq(P)=T0+?Rf(P)/Kprt, where T0 is crystal temperature at P=0. In present work temperature tuning curves of PPLN crystal and its phase matching temperature dependence on pump power (CW ytterbium fiber laser up to 25 W) were precisely measured in second harmonic generation experiment. Hysteresis of PPLN temperature and optical bistability of the second harmonic power in respect to pump power were observed.

8847-9, Session PMon

Band gap control of photonic crystal cell fabricated using block copolymer and hydrogel with electric field

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Optical and electrical characteristics of the devices using photonic gel film and hydrogel were studied. Poly(styrene-b-2-vinyl pyridine) (PS-b-P2VP, 52k g/mol – b - 57k g/mol) lamellar structure with alternating hydrophobic-block and hydrophilic-block polymers were prepared for the photonic crystal film. Poly(acrylamide-co-acrylic acid) sodium salts were prepared for the hydrogel. This hydrogel is water swelling material and it-owned ions for a device has conductivity. Photonic gel film was coated onto Indium tin oxide (ITO) glass for make electric fields by spin coater. The reflectance maximum wavelength of photonic crystal device shifted from 538 nm and reached to 557 nm, 585 nm and 604 nm during 30 min voltage applying time. The bandwidth variation was very limited. Loss of electrolyte was much less with hydrogel compared to the pure water. We can control color of photonic device by electric field with reasonable time range under moderate electric field by applying 2 V between two facing electrode.

8847-38, Session PMon

Mach-Zehnder interferometer in a rod-type photonic crystal

Maojin Yun, Meiling Liu, Feng xia, Wei Lv, Zan Zhang, Qingdao Univ. (China)

Photonic crystals have attracted great attention and quickly became the subject of extensive worldwide research due to their unique ability to manipulate light. The distinguished properties of photonic crystal, such as superlensing effect, negative refraction, and self-collimation effect have been widely studied. Self-collimation effect allows light propagation without diffraction in perfect photonic crystal. We propose a compact?high efficient photonic crystal Mach-Zehnder (MZ) interferometer based on the self-collimation and photonic band gap in a Rod-type Photonic Crystal . Line defected photonic crystals are used as the beam splitter and the mirror. Self-collimation frequency range is confirmed by using the plane wave expansion method. The interference is investigated with the finite difference time domain(FDTD) simulation technique, and the simulation results agree well with the theoretical prediction. Because of their small dimensions, the proposed MZ interferometer holds great potentials for applications in photonic integrated circuits.

8847-39, Session PMon

Focusing on the graded negative index lens by annular photonic crystal

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Focusing on the graded negative index lens made by annular photonic crystal (APC) is theoretically studied. The graded annular photonic crystal (GAPC) is composed of a dielectric-rod and a circular-air-hole array in a triangular lattice. The grade index is achieved by gradual modification of the radius of the rod along the transverse direction to propagation. The properties of the GAPC are analyzed by using the Plane Wave Expansion (PWE) method and the numerical simulation is studied by using the Finite-Difference Time-Domain (FDTD) method. Numerical simulation results show that the GAPC can realize the focus of plan waves and the focal length can be designed with the formula of modification and the wave frequency. The designed GAPC has the potential application for coupling with various types of waveguides.

8847-40, Session PMon

Optimization of high fixed diffraction efficiency in LiNbO3:Ce:Cu using optimal switching from recording to fixing

Peipei Hou, Ya'nan Zhi, Jianfeng Sun, Yu Zhou, Lijuan Wang, Wei Lu, Liren Liu, Shanghai Institute of Optics and Fine Mechanics (China)

Optimization of high fixed diffraction efficiency in LiNbO3:Ce:Cu is investigated. The nonvolatile holographic recording is realized in LiNbO3:Ce:Cu for different doped concentration. Holographic gratings are recorded using typical recording wavelengths including 488, 514, 633 and 799nm. There is an optimal switching time for the maximum diffraction efficiency up to an ideal of 100%. The fixed holograms are developed by an original recording setup. Diffraction efficiencies of recording and fixing are measured by a two-wave coupling technique. The experimental results are analyzed and compared. The optimal recording wavelength and doped concentration for high fixed diffraction efficiency is discussed in detail.Through the analyzed, the optimal recording wavelength and doped concentration for high fixing efficiency in LiNbO3:Ce:Cu is provided. This work can obtain high persistent diffraction of the nonvolatile holographic storage in LiNbO3:Ce:Cu crystals.

8847-41, Session PMon

High speed and low side lobe optical phased array steering by phase correction technique

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Laser beam scanners are important optical elements with a large variety of applications in the measurement techniques, optical communications, laser imaging ladar, etc. Agile beam steering of optical radiation using phased arrays offers significant advantages, such as weight, stability and power requirements over conventional beam steering systems. There are several kinds of optical phased array technology to be developed, such as Lithium tantalite phase shifters, lithium niobate electro-optic prism deflectors, and liquid crystal and ferroelectric liquid crystal phase modulations. However, one of the major drawbacks of these approaches is low light efficiencies because of the side lobes in far-field pattern of the steering beam.

In this paper, a new low side lobe optical beam steering technique using phase correction technique is proposed. A stable and fast single-lobed far-field pattern in steering beam can be obtained from the optical

phased array with a phase plate by optima design. It can result in a substantially increased light efficiency and beam quality. The quantitative calculation results of typical optical phased array are demonstrated. The low side lobe optical beam steering technology of optical phased array will benefit many practical applications such as laser ladar, laser communications and high resolution displays.

8847-42, Session PMon

Group delay properties of linear chirped Gaussian pulse diffracted by volume gratings

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Volume gratings are of wide interest in many applications because of their properties of high diffraction efficiency, excellent wavelength selectivity and angular selectivity. Ultrashort pulsed laser has many promising applications in the fields such as optical communication, signal and imaging processing. Because of its abundant spectrum and wide bandwidth, the diffraction properties of volume gratings under illumination by ultrashort optical pulse will be different from that of a monochromatic continuous wave. A periodical structure is highly dispersive and such a dispersive property can be used to control the group velocity of light beams. So the spectral properties and dispersive properties of the periodically layered structures such as volume gratings when a linear chirped Gaussian pulse illuminated are very necessary. These properties can be applicable to addressable filter, switching, and controllable optical delay line. In this paper, a detailed study of linear chirped ultrashort pulsed beams diffracted by volume gratings in dispersive media is performed. The group delay characteristics of the diffraction spectrum of the transmitted and reflected volume gratings were studied based on a modified coupled wave theory. The analysis and observation of this paper will be valuable for the designing optical elements based on diffractive structure for use with linear chirped ultra-short pulsed waves.

8847-43, Session PMon

Performance analysis of electrochromic coloration efficiency by the oxygen deficiency in the sputtering a-WOx films

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In this paper, we report on how electrochromic coloration is affected by oxygen deficient stoichiometries in amorphous tungsten oxide (a-WOx) films prepared by a dc reactive magnetron sputtering. The peak color efficient (CE) value of oxygen partial pressure at the optimum 6.5Exp(-3) Torr is improved about nine-fold larger than that of 2.0Exp(-3) Torr even in the nearly stoichiometric a-WOx films. We attributed that the optical absorption of a colored a-WOx film can be satisfactorily described by an intervalence charge-transfer transition (ICTT) mechanism between localized W5+ and W6+ states. Therefore, we have determined the most suitable condition (by increasing the partial oxygen pressure) to produce a-WOx films, thus offering a good electrochromic performance for opto-switching applications.

8847-44, Session PMon

Cochleate plastic photonic fiber

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In recent years, terahertz (THz) radiation has attaracted considerable interest using plastic photonic crystal fiber (PCF). PCFs consisting of waveguiding core and a cladding layer with spatially periodic air holes are currently another subject of intensive research. Compared with the conventional optical fibers, the PCF exhibits unusual optical properties, such as single-mode operation, anomalous dispersion, and large mode area.

We propose cocheleate plastic photonic fiber as a new design for THz optical fiber, Using finite difference time doamin computational strategy, the modal characteristics of the proposed fiber is analyzed. The proposed Teflon fiber is fabricated by using Teflon rod, tube and sheets. Teflon rod and tubes are arranged in a row on the adhesive Teflon sheet and rolled up tightly. As a result, cocheleate plastic photonic fiber is developed. By using a THz time domain spectroscopy technique, the propagation characteristics of sub-ps THz pulses are investigated

8847-45, Session PMon

Shifting selectivity of shift-multiplexing volume holographic storage system enhanced by unbalanced spherical wave

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Shifting multiplexing holographic storage system is compatible to traditional optical storage system since it only needs rotating the disk to apply multiplexing. Therefore, it is more possible to be commercialized. However, Bragg degeneracy causes series inter-page crosstalk. In this paper we propose spherical wave front with Astigmatism aberration to enhance the shift selectivity in the direction of Bragg degeneracy. The reference wave has an unbalanced wave front, which is divergent tangential direction (x direction) and convergent radial direction (y direction). The reference can be expressed as a line shape light source with divergent phase distribution in x direction and convergent phase distribution in y direction. We introduce Astigmatism in the reference beam to improve the shift selectivity in the direction of Bragg degeneracy. Experimental results are used to demonstrate the idea. For LiNbO3 locates 4mm away from the focusing line, we get balanced shift selectivity in both x and y direction. When central region in y direction of reference wave is blocked, the shift selectivity along y direction is enhanced to be 10?m.

8847-46, Session PMon

Effect of light intensity on quasi-nonvolatile holography in doubly doped LiNbO3:Fe:Ru crystal

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The doped LiNbO3 has been extensively studied as one of the most promising materials for volume holographic data storage systems. However, holographic grating recorded in LiNbO3 is usually volatile during readout. To overcome it, several techniques such as thermal fixing, electric fixing, and two center recording have been proposed so far.

Quasi-nonvolatile readout with extended lifetime is found in some doubly-doped LiNbO3 crystal including LiNbO3:Tb:Fe and LiNbO3:In:Fe crystals. Experimental investigations show that high asymmetry in grating buildup and readout erasure rates can be observed when one color holographic recording is performed in these crystals.

Quasi-nonvolatile readout can be observed in the oxidized LiNbO3:Fe:Ru crystal when one color holographic recording is performed. In this paper, we focus on the effect of the total recording and readout light intensity on quasi-nonvolatile holography is investigated experimentally. Different intensities are used in the recording process and readout process in the experiments. The results show that the grating lifetime can be greatly extended by decreasing recording and readout light. At last, the reason for the high asymmetry is explained qualitatively in terms of a multiple center model

8847-47, Session PMon

Density of modes maps for design of nonlinear photonic crystal devices

Igor V. Guryev, Igor A. Sukhoivanov, José Amparo Andrade Lucio, Oscar G. Ibarra Manzano, Univ. de Guanajuato (Mexico)

In this work we present numerical results on characterization of the transmitting properties of the PhC linear and nonlinear filters confined within the waveguide. Novel characteristics of the PhC filters such as density of modes (DOM) maps and transmission maps are computed, and their efficiency analyzed. Presented characteristics can be used as an auxiliary optimization tools to reduce optical losses when designing high-efficient integrated optical components.

The DOM maps have been computed by means of the plane wave expansion method (linear and non-dispersive case) and by the FDTD method (to take into account nonlinearity and the refractive index dispersion)

DOM maps obtained by the PWE method have been compared with the ones found by the FDTD which have demonstrated their full correspondence to the transmission spectra of the filter. The PWE results possess higher contrast and allows investigate in details the eigen-states properties and behavior. On the other hand, DOM computed by means of the FDTD method give better representation of an actual transmission spectra and can be applied for design of the nano-optical devices.

Computed DOM map of the nonlinear PhC (rods-in-air) demonstrated significant variation of the DOM at large radii of the filter holes due to a larger fill-factor of the nonlinear material.

Proposed DOM maps allow precise characterization and optimization of the PhC filter properties with much lower computation time as compared to the field computation inside the device.

8847-48, Session PMon

Defect soliton in two-dimensional optical Bessel potential

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Optical spatial solution is a self-trapped beam that exists by virtue of the balance between diffraction and nonlinearity in a Kerr-type media or photorefractive crystal. In this contribution, we studied the existence properties of defect solitons supported by Bessel potentials for different defects. Numerical results show that under different modulation depth for the defect intensity, the existing ranges of defect solitons are different; and the deeper the defect is, the narrower the existence range of the defect soliton is. We found that the stability domain of defect solitons broaden as the defect become shallow. To verify predictions of the above linear stability analysis, the evolution of some typical defect solitons over a certain distance in the medium is obtained by dint of the split step Fourier method.

8847-49, Session PMon

Influence of magnetic field on fiber Bragg gratings in silica-based fibers at the temperature range 77-293 K

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Optical sensors based on fiber Bragg gratings (FBGs) are capable to measure very accurately temperature, strain, pressure, and acceleration while being immune to external electromagnetic interference. As a part of the graduate student research project an apparatus to interrogate optical sensors with embedded FBGs at the temperatures of liquid nitrogen and above and also at moderate magnetic field (900-8000 G) has been designed at Physics department of UA. The purpose of this work was to study the influence of the magnetic field on the performance of FBSs at the temperature range 77-293 K. Two different wavelengths (514.5 and 488.0 nm) have been used to monitor the state of transmitted light polarization with temperature with the emphasis on Faraday's effect under these conditions. It has been established that strong competition between elliptical and linear states of polarization has occurred and accompanied by increase of the transmitted power (for any polarization) with the peak at the vicinity of 200 K. This anomalous behavior has been compared with LP modal distribution of light at the same temperature range. The composition of the LP modes and their competition is important for understanding physics of thermo-optics and thermal expansion effects in silica-based fibers at low temperatures. Therefore a theoretical analysis of the computer-generated LP modes has been conducted and compared with experimental data.

8847-50, Session PMon

Dynamic characteristics of two-dimensional finite boundary photorefractive gratings recording and fixing in LiNbO3:Fe crystals

Conglin Lv, Zhijuan Hu, Aimin Yan, Yadong Jin, Huili Chen, Shanghai Normal Univ. (China); Jianfeng Sun, Shanghai Institute of Optics and Fine Mechanics (China)

Nonvolatile photorefractive holographic recording has been widely studied and regarded as the most promising technique for holographic storage, which also has the important potentials in the multifunctional integrated 3-D optical system. However, in practical applications, there still are some crucial problems, such as hologram readout erasing stored information (volatility), low diffraction efficiency, and so on. Fixing the refractive-index grating as one of the key issues for volume holographic memory has become a popular research direction. Thermal fixing is by far the most popular and effective technique for storing nonvolatile photorefractive memories in LiNbO3:Fe crystals. For optimizing the holographic recording in singly doped LiNbO3 crystals, the diffraction characteristics of crossed-beam photorefractive grating are required, and the optimal recording condition should be analyzed. In this paper, some dynamic diffraction characteristics of crossed-beam photorefractive holograms in Fe doped LiNbO3 crystal are studied based on jointly solving the material equations and the two-dimensional coupled-wave theory. The temporal and the spatial evolutions of the refraction index modulation and the diffraction efficiency are given. The spatial variation of the wave intensity is also presented. The influence of the recording conditions, including the optimal recording wavelength, the widths of the recording beams, the width ration of recording beams, and the intensity of recording beams are discussed in detail. We also discussed the dynamic from the recording step to the thermal fixing step. The analysis and observations of this paper will provide some valuable approach to obtaining high persistent diffraction of the nonvolatile holographic storage in doped LiNbO3 crystal.

8847-51, Session PMon

A novel implementation of optical fiber as converging lens and passive optical clock circuit

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In this paper we report implementation of optical fiber as converging lens and passive optical generating 100-200 Giga pulses per seconds repetition rate . In brief a tapered fiber having input hole several hundred times greater than output hole and enough length to give enough converging angle that no back scattering occurs, was tested as converging lens. This lens which has output radius of several micrometers can couple and concentrate output beam of a laser to the output. By implementation of hundreds sequences of "1 to n" i.e. ("1*n" optical fiber splitter) the input signal is divided -that can be a giant optical pulse – to "n" output and each time is fed to "n" numbers of output fibers, roughly each output will have intensity of 1/n of input optical pulse and at final stage each branch has only several micrometers length difference in compare with the previous output. This outputs constitute a bundle of hundreds or thousands of micro-fibers then all of these go the reverse stage. All coupled by the same stages of "n to 1" (i.e. n*1 optical couplers). At the final stages due to precise difference length of each branch that makes a delay about several femtoseconds in respect to previous signal, the Output signal will be a sequence of pulses having intensity of equal to (1/ n* number of stages) and repetition rate of thousands of Ghz (Giga pulses per seconds). All non-linear effects during propagation are discussed in the paper.

8847-52, Session PMon

Multipoint side illuminated absorption based optical fiber sensor

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A simple, compact, low cost, multiple point optical fiber sensor for relative humidity (RH) was demonstrated. It has a spatial resolution of 5 mm or better, and can be used for measurements in air, soil, concrete and any other environment where RH is a concern. This sensor uses side illumination of an optical fiber to probe multiple points along the fiber length.

A 1mm diameter glass core fiber and plastic cladding (Thor Labs' BFL48-1000), 25 cm long, was used. Three sections of the original fiber coating and cladding were removed and a polyvinyl acetate solution, with the reversible RH indicator Reichardt's dye, was prepared and applied over these sections creating the sensitive regions. The fiber was mounted over a 20cm long plastic support having three white light LEDs that illuminated each sensing point. The optical signal was coupled into the fiber core and transmitted to a silicon detector located at the fiber tip.

A glove box, model 503 from Electro Technical Systems, connected to a desiccant, an ultrasound humidifier, a control unit and an NIST traceable RH sensor was used for calibration. The light intensity was found to increase linearly with humidity and a resolution of up to 0.15% was obtained.

This concept can be used to design highly dense multi point multi parametric sensors with 200 sensing points, or more, for each meter of fiber. It can be and have been extended to other parameters such as pH, nitrate, phosphate, potassium, magnesium, calcium and others.

8847-53, Session PMon

Flat optical lens by use of 90-degree volume holographic grating recording geometry and nonvolatile thermal fixing in LiNbO3:Fe crystal

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A new design and fabrication of flat optical lens by use of 90-degree volume holographic grating recording geometry is presented. It is recorded by the interference of a plane wave and a spherical wave in a Fe-doped LiNbO3. The flat optical lens can laterally spread and focus the plane wave which perpendicularly incidents on the planar crystal surface. On the basis of the coupled- wave theory of local volume holography. the amplitude distribution and the diffraction efficiency of the diffracted beams are calculated. The optimal switching from recording to thermal fixing is taken into consideration in order to obtain the nonvolatile hologram with maximum fixing efficiency. The flat optical lens has the advantages of light weight, laterally-spreading and focusing, small duty ratio, and easy for the microstructure integration. The testing results measured verify that the flat optical lens can successfully be used for the free space optical communication.

8847-54, Session PMon

Holographically amplified interferometry with coherent fringe projection for the oil on the water remote sensing and characterization

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We suggest combining several optical methods of remote sensing and characterization of crude oil films and emulsions: coherent fringe projection illumination (CFP), holographic in-line interferometry (HILI) with proposed holographic amplification of weak signal images. Combined methods of CFP and HILI are described in the frame of coherent superposition of partial interference patterns. Theoretical approach is illustrated by introducing of the scattering diagrams, describing partial contribution of different interference patterns. We also evaluated different alternative schemes of interferometry with holographic recording and preliminary holographic amplification in photorefractive crystals. Holographic amplification of weak images without phase distortions is possible in a special mode of holographic recording in photorefractive crystals. This preliminary amplification of weak signal beam do not change phase of the signal wave and allow further digital registration and processing with improving signal to noise ratio. Combination of dynamic holographic amplification with digital processing may be especially effective for detection and characterization of weak reflected signals from biological objects. Comparisons of theoretical and experimental results allow finding size of the oil spot and estimating oil film thickness.

8847-55, Session PMon

3D shape measurements for non-diffusive objects using fringe projection techniques

Wei-Hung Su, Zhao-Kai Wang, National Sun Yat-Sen Univ. (Taiwan)

A scanning approach using fringe projection techniques to perform the 3D profile measurement of a non-diffusive object is proposed. Experimental results are presented that demonstrate the shape measurements of objects with non-diffusive surfaces.

8847-56, Session PMon

Using a phase mask to reduce the depth-of-field of the image acquisition system and its application to 3D shape measurements

Wei-Hung Su, National Sun Yat-Sen Univ. (Taiwan); Nai-Jen Cheng, National Kaohsiung Univ. of Applied Sciences (Taiwan)

In this paper, we present a scanning approach to retrieve the 3D shape of the object with depth height discontinuities. A phase mask is used to reduce the depth-of-field of the image acquisition system. The depth-of-field of the system is so short that only surfaces within the focused area can be clearly observed. By moving the inspected object around the focused area along the depth direction, a set of images which addresses the contour of the object with its corresponding depth is obtained. The

3D shape of the object is retrieved by assembling the image contours with their corresponding depths.

8847-57, Session PMon

Plasmon-active mixed gratings in volume holographic polymer nanocomposites

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Holographic data storage technology has been considered as a promising next-generation memory for its unique advantages of large storage capacity and high data transfer rate [1]. With angle multiplexing technology based on Bragg diffraction, thousands of pages of optical information can be superimposed and recorded at a common volume of recording material [2]. In such a memory system, a thick recording material with high diffraction efficiency and low cross-talk noise is key component to achieve large storage capacity. Compared with other types of holographic materials, photopolymer is an optimum material for practical holographic applications due to its high dynamic range, dry real-time processing and low cost [3]. Tremendous efforts have been spent on improving the holographic performances of photopolymer. However, the cross-talk noise induced by the side lobes of angular selectivity is usually unavoidable for the volume holographic grating, which limits the storage capacity in angle multiplexing holographic memory system. It has been known that gold NPs exhibit significant enhancement on absorption due to the collective excitation of conducting electrons known as surface plasmons [4]. In principle, the volume holographic gratings with a modulation of the absorption coefficient can affect the profile of holographic recorded grating. In this letter, we present a novel holographic nanocomposite with the improved holographic diffraction efficiency and suppressed side lobes of angle selectivity by dispersing gold nanoparticles into a bulk holographic photopolymer. The strong absorption grating as a result of redistribution and strongly absorption of gold nanoparticles is activated in phase with the intrinsic refractive index grating. The characteristics of plasmon-active mixed grating are simulated through Kogelnik's coupled wave model. The improved holographic performances are also demonstrated in the volume holographic polymer nanocomposites. It may open up a new way to design the functional holographic material by improving the coupling between the light wave and sub-micrometer patterns.

8847-58, Session PMon

Time domain modeling of induced birefringence and phase shift in piezoelectric resonance enhanced electrooptic modulators

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In our continuing effort of developing electromagnetic-electromechanical-electrooptic interactive devices, the effect of piezoelectric resonance on the performance of electrooptic modulators is investigated. Time domain finite element models were constructed to determine the phase shift due to the induced birefringence of the device. Two sinusoidal voltage sources are used one to sweep over a range of frequencies while the other setting the modulator at a selected resonance frequency. Ferroelectric single crystals such as $LiNbO_3$ and $(Pb,Zn)NbO_3$-$PbTiO_3$, were examined for their induced index of refraction, the induced phase shift, and the half-wave voltage of given configurations. The time domain model of dual signal ac biased configuration displayed wide bandwidth enhancement when biased at proper resonant modes, which matches well with experimental observations. The results demonstrate the piezoresonant enhancement in terms of low half wave voltage and high electrooptic coefficients in broad frequency ranges. The results also provided corresponding insights that further our understanding on experimental observations reported previously by the authors. The models are suitable for designing of electrooptic device configurations that optimize the properties desired.

8847-59, Session PMon

A simple optical probing technique for nonlinearly induced refractive index

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Self phase modulation is a nonlinear effects that is observed when a laser beam is focused on to a high-absorbing thermal medium. The refractive index of the medium changes due to the heat generated by the focused laser pump beam. In this paper, self phase modulation is investigated in different ways. An Ar-Ion laser of 514 nm is used as the pump beam and a 632 nm He-Ne laser is used as the probe beam. The probe beam is introduced from the opposite side of the pump beam. Ring patterns are observed from the each side of the sample. Regular far field ring patterns are observed from the pump beam, and two sets of rings are observed with the probe beam. The behavior of these inner and outer rings are monitored for different pump powers. A regular tea sample in a plastic cuvette is used as the nonlinear absorbing sample. The steady state heat equation is solved to obtain an exact solution for the radial heat distribution and far field ring patterns are simulated using the Fresnel–Kirchhoff diffraction integral. Ring patterns are theoretically explained using simulations results, and compared with experimental observations. Finally, an interferometric setup using the low power He-Ne laser is also used to determine the induced change in refractive index. Results are compared with those obtained directly from self-phase modulation and from the probe beam method.

8847-60, Session PMon

Large-core single-mode trench assisted leaky channel waveguide for high-power applications

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A suitable waveguide design for high-power laser is one which can support only single- mode for propagation even with a suitably large more area. In this paper we have presented a large-mode-area design in channel waveguide for extended single-mode operation. Proposed design is characterized by a rectangular core and trench assisted cladding. Overall design is leaky and supports a finite leakage loss to all the modes of waveguide. Leaky cladding consists of three trenches of variable depth and thickness. Depth of the trench decreases as one move away from the rectangular core. Proposed design works on the principle of mode filtering. Performance of the waveguide depends upon the leakage losses of the first two modes. We have calculated the leakage loss of the modes using effective-index method. We have made the comprehensive analyses of the trench parameters on the leakage losses of the modes and hence the SM operation. A polymer waveguide with parameters: n1=1.444, n2=1.542, n3 = 1.512, a =5 um, h=10 um, d1=3 um, d2=2 um, d3= 5um introduces 20dB/mm to mode while a nominal loss of 0.20 dB/mm to fundamental mode. Thus, a 1 mm length of waveguide can strip off all higher-order modes to ensure effective single-mode operation with mode area as large as 100 um^2. Dispersive cladding ensures single-mode operation in the wavelength range 750-1600 nm. Proposed waveguide can be fabricated in polymer geometry by reactive-ion etching technique and is expected to find applications in designing high-power lasers.

8847-61, Session PMon

Selectively filled large-mode-area photonic crystal fiber for high power applications

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In the last decades photonic crystal fibers (PCFs) remained exciting research topic because of their unique features such as endlessly single mode, dispersion tailoring, high birefringence, large mode area etc. Among these features of PCFs large mode area (LMA) is most important because it support high power transmission in the fiber lasers, fiber amplifiers and other high power applications. The limitations of high power devices are the nonlinear effects and the low threshold frequency value. These limitations may be overcome by using fiber with large mode area that can maintain single mode operation. In this work we have proposed a PCF design in which the center air hole has been removed and the six air holes near the center core are filled with high refractive index material. To analyse the design we have used Finite Element Method. Transmission characteristics of PCF such as effective mode area, single-mode operation and bending performance of the fiber have been investigated for varying the geometrical parameters. Selectively filled material of refractive indices, nfill, 1.451 and 1.4515 has been chosen to analyse the performance of the proposed design. Spectral performance of the design has also been investigated for both the filling material. Effective mode area of the fundamental mode increase with the wavelength. Proposed design with nfill = 1.451 show 835 um^2 mode area at 1.064 um with a nominal loss of 1.0e-4 dB/m at 10 cm bending radius. Such fiber can be a good candidate for design of high-power applications.

8847-62, Session PMon

Ferroelectric memory element based on thin film field effect transistor

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Ferroelectric field-effect transistors (FET) using ZnO:Li films as a FET channel and as a ferroelectric active element simultaneously are fabricated and studied. A possibility for using of ferroelectric field-effect transistor based on the ZnO:Li films in the ZnO:Li/LaB6 heterostructure as a bi-stable memory element for information recording is shown. The proposed ferroelectric memory structure does not manifest a fatigue after multiple readout of once recorded information. The latter allows one increasing of the memory resources.

8847-63, Session PMon

Electronic phase transitions in transparent zinc oxide thin films

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Metal?dielectric electronic phase transitions in wide gap ZnO semiconductors have been studied. The influence of defect complex caused by oxygen vacancy and interstitial zinc atom on the metal-dielectric transition is considered. The peculiarities of this transition in ZnO films doped by donor or acceptor impurity and the influence of mentioned defect complex on the charge carrier transfer mechanism were investigated. The control parameter of this transition is the concentration of Zn interstitial atom. The films with high concentration of Zn interstitial atom have high conductivity of metallic type. Air annealing leads to conductivity decreasing and to change of conductivity temperature dependence from metallic type to semiconductor (dielectric) one.

8847-64, Session PMon

Tomographic study of polymer bridges between two optical fibers for telecommunication applications

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The most common methods of optical fibers joining are fusion splices and mechanical splices with refractive index-matching gel between the fibers ends. A new, simple method of manufacturing micrometer-sized polymer waveguides – bridges – between two optical fibers, which has been reported a few years ago, could greatly improve mechanical splicing efficiency. A drop of a liquid photopolymerizable formulation is deposited between two cleaved fibers and the polymerization process is induced by the light that emerges from one of the fibers. Waveguide effect inside the polymer creates a stable connection between fibers' cores. After removing the excess of unpolymerized formulation, another type of photopolymerizable solution is introduced to the splicing area to create protection cladding.

Investigation of the detailed index profile obtained allows to describe the light propagation in the waveguide and to deduce its performances: insertion losses and reflection losses of the bridge.

In this paper we present studies of interferometric tomography used to determine the refractive index distribution in the polymer bridges.

Detailed refractive index maps are needed in order to improve the technological process of manufacturing those bridges and achieve lower reflection losses. Our investigations are performed in several stages.

At first the insertion and reflection losses are measured to check if the bridges have the assumed optical properties. The next step is to perform full tomographic measurements in a Mach-Zehnder based interferometric tomography setup for both bridges and reference fibers used to produce those bridges. The latter provides refractive index distributions and profiles. Based on these data we use several commercial modeling tools in order to obtain reflection and insertion losses. The obtained values will then be compared to those obtained by usual reflectometry.

8847-65, Session PMon

In addition of acousto-optic devices' piezoelectric transducers design issue

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Acousto-optic device are used in various signal processing systems and laser radiation controlling systems. These systems allow the wideband signals processing in real-time and high-speed laser beam scanning.

The main technical difficulties caused by technological problems of its production, such as attaching the piezoelectric transducer for efficient excitation of acoustic waves in crystals in the range of 100-1000 MHz.

In this range there usually use a lithium niobate crystal plates as the active piezoelectric excitation of longitudinal waves or shear waves, and thin films of zinc oxide there usually use for the higher-frequency acousto-optic devices.

It is shown that it is possible to choose slices of piezoelectric transducers for some devices that will generate both types of oscillation, L and S simultaneously. It is Y +12° and Y +137° slices. Also this article shows that for reducing the level of excitation of parasitic oscillations requires high accuracy of the crystallographic orientation of the plates.

In this paper, dependences of electromechanical coupling coefficient for different slices of a lithium niobate crystals are calculated. They illustrate the validity of selecting the appropriate cut for the piezoelectric transducer for the excitation of longitudinal waves and shear waves in acousto-optic cells.

Also, these dependences determines the criteria for the accuracy of the technological requirements for the piezoelectric plate transducers constructing.

8848-1, Session 1

Two-dimensional sub-5 nm hard x-ray focusing with MZP

Markus Osterhoff, Matthias Bartels, Florian Döring, Christian Eberl, Sarah Hoffmann, Tobias Liese, Volker Radisch, Anna-Lena Robisch, Aike Ruhlandt, Felix Schlenkrich, Tim Salditt, Hans-Ulrich Krebs, Georg-August-Univ. Göttingen (Germany)

To date, sub-10 nm focusing has been achieved using Multilayer mirrors, and sub-50 nm focusing is routinely achieved using Multilayer zone plates and Multilayer mirrors. Numerical simulations of optimised focusing devices reach below the 1 nm scale.

Here, we show that a combined optic of a large-aperture Kirckpatrick-Baez mirror system in conjunction with small focal lengths of a multilayer zone plate, enables two-dimensional focusing below 5 nm (FWHM).

The concept preserves the benefits, while overcoming the limitations, of two schemes: KB mirrors offer large accepting apertures of the incoming X-ray beam, but have a large focal length; MZPs are very compact with focal distances in the micrometre range.

Therefore, aperiodic W/Si multilayers were pulsed laser deposited (PLD with high quality on a W wire with single layer thickness down to 5.1 nm. From the coated wire, a lens of thickness 700 nm was fabricated by cutting using focused ion beam (FIB). X-ray focusing experiments were performed at the coherence beamline P10 of PETRA III at a photon energy of 7.9 keV, corresponding to a wavelength of ?=0.159 nm.

In a first demonstration experiment we recorded far-field diffraction patterns that are consistent with a 2D focus of 4.3 nm x 4.7 nm, with a focusing efficiency of approximately 1 %; forward simulations including error models based on measured deviations, auto-correlation analysis and three-plane phase reconstruction are in good agreement.

8848-2, Session 1

Development of ultra-precise piezoelectric deformable mirrors for x-ray nanofocusing

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We designed and fabricated a piezoelectric deformable mirror without high-spatial-frequency deformation errors. To investigate the performance of the developed deformable mirror, the deformation accuracy was evaluated when the mirror was deformed to an elliptical shape. A peak-to-valley deformation accuracy of 2 nm was achieved. In addition, to investigate its focusing performance, we performed a two-dimensional focusing test at SPring-8. As a result, a focus spot size of 300 nm (H) x 490 nm (V) was realized.

8848-3, Session 1

Thin crystal development and applications for hard x-ray free-electron lasers

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Development of thin crystals, which can be utilized as beam splitters for the hard x-ray regime, is important for expanding the range of applications of hard x-ray free-electron laser (XFEL) sources. In particular, a beam splitter is used to construct a split and delay unit, which produces two replica XFEL pulses with a time delay from femtosecond to nanosecond, and to provide a dedicated branch for photon diagnostics. To function as a beam splitter, the crystal device has to be a perfect single crystal with a thickness from a few to 20 µm to obtain high reflectivity and transmissivity, simultaneously. Fabrication of the crystal is difficult with conventional methods. We developed a new method to fabricate a thin silicon crystal based on a reactive dry etching method using atmospheric-pressure plasma. Owing to the high pressure, ions in the plasma have low kinetic energy, which suppress to induce lattice strains. Another advantage of this method is a capability to etch the silicon target isotropically with a processing speed that is independent of crystal orientations [e.g., (111) or (511)]. Using this method, we succeeded in fabrication of sub 10-µm-thick Si crystals. High crystalline perfection of the crystals was verified with topographic and diffractometric methods using coherent x-rays at the 1-km-long beamline BL29XU of SPring-8. We report the results and several applications of the thin crystals at SPring-8 Angstrom Compact free-electron LAser (SACLA).

8848-4, Session 1

Design of novel x-ray optical system for rocket experiment

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In this work, a novel design of X-ray optical system for astrophysical rocket experiment is investigated. The proposed system is based on four modules with Kirkpatrick-Baez (KB) configuration allowing usage of multi-foil mirrors arranged to parabolic profile. The KB modules are supplemented by rotationally symmetrical parabolic segments. This X-ray optical system effectively uses a circular aperture. The KB modules are placed in four quadrants while the segments are set into a Cartesian cross between the KB modules. The proposed optical system could be used within a student rocket experiment of University of Colorado that should verify function of NIST's energy-dispersive detector based on Transition Edge Sensors (TES microcalorimeters).

8848-5, Session 1

High-speed photon energy tuning of x-rays with high duty cycle by use of clessidra prism arrays

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Clessidra x-ray lenses are formed of many tiny prisms in rows, which are arranged in the form of a large prism. Such objects can focus x-rays by refraction when the number of prisms increases appropriately with increasing distance from the lens optical axis. The refractive index of matter for x-rays varies rapidly with photon energy, and consequently these objects focus chromatically. They can thus even act as monochromators in combination with slits in the focal plane, as was shown by Liu et al (J. Synchrotron Rad. 19, 191–197 (2012)). The simplest energy tuning is achieved, when the exit slit is moved longitudinally along the beam trajectory. As this is inconvenient, Jark (J. Synchrotron Rad. 19, 492-496 (2012)) proposes the photon energy tuning in a fixed slit by varying the azimuthal orientation of the structure, or its yaw angle, with respect to the incident x-ray beam. This will then require a wider prism structure. Now the symmetry of the clessidra structure can very favorably be used for the construction of a high speed monochromator with very efficient duty cycle. The lens structures are rather small with dimensions of the order of 1 mm in height and 25 mm in width and in length, and can thus easily be rotated in yaw with high speed. This contribution will discuss various options of this operation scheme.

8848-6, Session 2

Hard x-ray nanofocusing with refractive x-ray optics: full beam characterization by ptychographic imaging

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Hard x-ray scanning microscopy relies on small and intensive nanobeams. Refractive x-ray lenses are well suited to generate hard x-ray beams with lateral dimensions of 100 nm and below. We have used both rotationally parabolic refractive x-ray lenses made of beryllium and nanofocusing refractive x-ray lenses (parabolic cylinders) made of silicon to focus hard x-rays between 8 and 25 keV to (sub-)100 nm dimensions. With rotationally parabolic refractive x-ray lenses, a lateral full-width at half maximum (fwhm) extension of 125 to 400 nm was achieved, showing consistently the dependence of diffraction limited focus size and depth of focus on the aperture of the optic. With nanofocusing refractive x-ray lenses, beam sizes down to 46 nm were achieved. The nanobeams were fully characterized by ptychographic scanning coherent diffraction imaging, giving access to the full complex wave field in the focus with unprecedented accuracy and sensitivity. From these data, we can reconstruct the caustic along the optical axis and determine the aberrations of the x-ray optics. By verifying the consistency of several independent wave field measurements along the optical axis, we address the question of how well the reconstruction represents the nanobeam. With a single ptychogram the wave field can be properly determined over a large range along the optical axis, also at positions inaccessible otherwise.

8848-7, Session 2

X-ray tomography of high-pressure fuel spray by polycapillary optics

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In this paper the structure of a gasoline spray from an automotive GDI injection system has been studied by means X-ray Tomography.

The study of transient high pressure fuel sprays by X-ray based techniques is worldwide diffused. Synchrotron radiation is successfully exploited for this aim because of its high intensity and pulsed nature. However top-table application are unusual.

This work reports the results obtained by performing desktop experiments using an 8 keV Cu K∞ X-ray. Polycapillary semilens shaped the divergent X-ray beam into quasi-parallel one allowing to focus the radiation on the investigated spray region. High contrast focus images were collected by a CCD detector for X-radiation.

A 6-hole GDI injector has been coupled to the high pressure pump by a specially designed rotating device able to work up to 25MPa. X-ray absorption measurements have been performed with angular steps of 1° at the injection pressure of 12.0 MPa. The sinogram reconstruction of the jets by slices permitted to get information about the inner structure of the fuel spray downstream the nozzle tip, where conventional optical techniques are inhibited. A 3D spatial distribution of the fuel emerging from the injector has been obtained. The data have been used to perform spray density measurements. The results concerning the density profile along the fuel jets axis and the cross section distribution at different distances from the nozzle have been reported.

8848-8, Session 2

Sagital focusing-inducing energy structure in medium- to high-energy resolution x-ray monochromators

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Sagital focusing is widely used geometry to focus horizontally X-rays in synchrotron beamlines. Usually, two types of devices are used: toroidal mirrors combined with flat X-ray monochromators or flat mirrors combined with sagital focusing monochromators. The former option seems to be better since the stresses caused bending the second crystal in a double crystal monochromator (DCM) is avoided. In this work we exploit the effect of the sagital focusing in the medium to high energy resolution X-ray monochromators. Our studies are based on theoretical explanation of experimental data acquired into two different experiments made at XRD2 beamline at Laboratorio Nacional de Luz Sincrotron (LNLS / Brazilian Synchrotron) and X18A at National Synchrotron Light Source (NSLS / BNL / USA). The first experiment was carried out with a flat meridional bendable mirror followed by a DCM with the second crystal being sagitally bent. The second experiment was carried out with a flat Si 111 DCM followed by a toroidal, but meridional bendable mirror. Both setups are completed by a Si 551 4-bounce monochromator to scan the energy spectrum around 13.7 keV and 13.9 keV, respectively. The results show that the sagital curvature induces an energy structure. Theoretical studies made by analyzing the reflecting angles in the mirror surface joined with the dynamical theory of X-ray diffraction in the 4-bounce X-ray monochromators confirm these results which are also exploited by Dumond diagram analysis.

8848-9, Session 2

Modeling of compound refractive lens using Zemax software

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Compound refractive lenses (CRLs) developed over the past 20 years have successfully been used for 1D and 2D focusing of X-ray beams at synchrotron radiation facilities.

For an ideal CRL system, the focal distance, focus size, transmission, and the gain can be estimated using simple analytical formulations (e.g., the thin lens approximation). However, numerical techniques such as ray tracing may have to be employed to determine the impact that the lens (its imperfection, thickness, location, alignment) or the source (size, shape, properties) may have on the lens system performance.

In this paper the ray tracing software Zemax is used to analyze the performance of 'real' CRL systems with curved and saw tooth geometries, and investigate the impact of the aforementioned factor on their performance. The optimal design of a saw-tooth CRL for focusing a high energy X-ray beam is described, and experimental results are provided.

Work is supported by the U.S. Department of Energy, Office of Science, Contract No. DE-AC02-06CH11357.

8848-10, Session 3

K-B bendable system optimization at FERMI@ Elettra FEL: impact of different spatial wavelengths on the spot-size

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FERMI@Elettra, the first seeded EUV-SXR free electron laser (FEL) user facility, located at Elettra- Sincrotrone Trieste S.C.p.A., is under advanced commissioning. The Diffraction and Projection Imaging (DiProI) is one of the three beamlines already operative at FERMI@Elettra. It employs a Kirkpatrick-Baez (K-B) active X-ray optics system in order to focus the FEL beam on the sample inside the endstation. The aim of the present work is to characterize this optical system in order to improve and optimize its performances in terms of quality and size of the focal spot, and consequently of fluence. To this end, we performed a campaign of measurements with several diagnostic systems, including a wavefront sensor mounted after the DiProI chamber. Online wave- front measurements allow for optimizing the bending acting on the mirrors' curvature and the angle positions (pitch, roll, and incidence angle) of the K-B system. We have also compared the measurement results with the predictions from simulations obtained using the WISE code, starting from mirror actual surface metrology characterization. By filtering the Fourier transform of the mirror surface profiles we have analyzed the impact of different spatial wavelengths on the focal spot degradation. From wavefront measurements we have inferred a focal spot of 10 µm x 13.5 µm confirmed by the PMMA ablation. The results from simulations with the WISE code are in agreement with the measurements and show, for different energies of the incident beam, the threshold below which the spatial wavelengths of the K-B mirror surfaces start to have no influence on the focal spot degradation.

8848-11, Session 3

Fabrication of ellipsoidal focusing mirrors for soft x-ray microscopy using elastic emission machining and electroforming

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Ellipsoidal mirror is one of promising soft X-ray focusing optics, because soft X-rays can be focused to nanometer dimension with very large aperture, long focal length and no chromatic aberration. However, the a nanometer focused beam size was not achieved. The reason is that there is no fabrication method of the inner surface with nanometer accuracy, in particular, when the diameter is less than several millimeters. We have been researching on manufacturing process of an ellipsoidal mirror for soft X-ray focusing. In this process, the master surface is fabricated through several steps consisting on grinding, polishing and Elastic Emission Machining (EEM). EEM can finish the surface shape with a controllability of 0.1 nm and the surface roughness less than 0.2 nm (RMS). Then the shape of ellipsoidal mirrors is produced by replicating the master surface using an ultra-precise Ni electroforming method. The electroforming is performed under a room temperature and the inner stress of the deposited film is adjusted to be extremely small by controlling electric potential on the films to realize high replication accuracy. In this paper, we report the current status in developments of EEM and electroforming processes specialized for ellipsoidal mirrors.

8848-12, Session 3

Two-foci bendable mirrors for the ALS MAESTRO beamline: design and metrology characterization and optimal tuning of the mirror benders

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MAESTRO, the Microscopic and Electronic STRucture Observatory, currently in the construction phase at the ALS, will be a world premier facility for the study of electronic and structural properties of in situ grown crystals. The new facility will be comprised of several end-stations, including angle-resolved photoemission spectroscopy (ARPES), sample sizes > 10 µm (µARPES end-station), sample sizes > 50 nm (nARPES end-station), and a photoemission electron microscope combined with a low-energy electron microscope (PEEM/LEEM). Redirection of the x-ray beam between the µARPES and PEEM/LEEM end-stations, which are longitudinally separated by 2.5 meters, uses a system of two bendable mirrors, placed in Kirkpatrick-Baez configuration. Here we present the details of the mirrors' design and report on the characterization of the mirrors carried out at the ALS optical metrology laboratory (OML). Optimal tuning and calibration of the mirrors was performed using a technique based on regression analysis of surface slope data obtained with a slope measuring long trace profiler (LTP) recently developed at the OML [Opt. Eng. 48(8), 083601 (2009)]. We provide results of tests of temporal and temperature stabilities of the shape of the mirrors. High reliability of the optical metrology with the mirrors has become possible due to a modification of the tuning procedure described in the present article. The modification allows accounting for the gravity sag effect, as well as the LTP systematic error in measurements with significantly curved x-ray optics. This work is supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

8848-13, Session 3

Optical design of two-step soft x-ray focusing system with rotationally symmetric mirrors

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Nano-focusing technique with high efficiency is required for high spatial resolution and high detection sensibility in various soft X-ray analysis methods. Rotationally symmetric-shape mirror, like an ellipsoidal mirror or a Wolter mirror, is the ideal focusing optics from the viewpoints of advantages of large aperture, long focal length and no chromatic aberration. However, there are a few problems when these mirrors will be installed to a synchrotron beamline. The beam size of incident soft X-rays from the source is too small to illuminate the entire surface, which denotes that the numerical aperture decreases and soft X-rays cannot be focused to the desired size. To solve this problem, we propose two-stage focusing system using a free-form grazing incidence mirror and a rotationally symmetric mirror for expanding and focusing, respectively. Generally, the X-ray beam propagating at the central region of the rotationally symmetric mirror cannot be utilized. In the proposed optical system, the soft X-ray beam reflected by the upstream mirror is focused with a ring-shaped intensity distribution on the focal plane and expanded with dark area at the center to illuminate the entire surface of downstream

mirror with no loss of photons. As the results, soft X-rays can be focused with high numerical aperture with high efficiency. The degree of freedom against the geometrical limit is also further increased in optical designs. This paper reports a design procedure to determine the shape of both mirrors and results of ray tracing and wave optical simulations at water window wavelength ranges.

8848-14, Session 3

Dual focusing for hard-x-ray inelastic scattering

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We use a combination of a bent cylindrical mirror and short (15 and 20 cm) elliptically polished Kirkpatrick-Baez (KB) mirrors to efficiently focus the entire beam from an insertion device for flux-limited inelastic x-ray scattering experiments at energies up to 26 keV. This system is in regular use at SPring-8 BL35XU. Use of only the bent cylinder, 10 meters from the sample, provides a small spot, ~70 microns diameter, with good, ~0.35 mrad, collimation and nearly 100% throughput over an acceptance of more than 4 x 1.5 mm2 in most experiments. Insertion of an additional KB pair, without moving the sample position, reduces the spot size to 16 microns, for samples where a smaller spot size is desirable, even at the expense of poorer momentum resolution, due to increased divergence. The KB pair employs fixed elliptically polished mirrors and pre-focusing from the cylindrical mirror is used to realize a relatively inexpensive setup that retains high (~50%) throughput compared to the full ID beam, even at energies above 20 keV. Design considerations, and the setup, and the performance of the system will be discussed, including the choice of elliptical KB mirrors instead of hyperbolic mirrors, and the strict limits set by requiring large (180 mm) free space upstream of the sample position.

8848-15, Session 4

X-ray mirror metrology using SCOTS/ deflectometry

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SCOTS is a high precision slope measurement technology based on deflectometry. Light pattern on a LCD display illuminates the test surface and its reflected image is used to calculate the surface slope. SCOTS provides a high dynamic range full field measurement of the optics without null optics required.

In this paper, we report SCOTS tests on x-ray mirrors to sub nm level with precise calibration of the test system. A LCD screen with dots/check board pattern was aligned into the system at the test mirror position to calibrate camera imaging distortion in-situ. System errors were further eliminated by testing and subtracting a reference flat which was also aligned at the same position as the test mirror. A virtual reference based on the ideal shape of the test surface was calculated and subtracted from the test raw data. This makes the test a 'virtual null' test. Better than 0.1nm rms precision and sub nm rms accuracy were achieved on a super polished elliptical mirror (90mm in its long end). The test accuracy is limited by the shape errors in the reference flat.

In comparison with sub-aperture stitching interferometry and long trace profilometer (LTP), commonly metrology used for X-ray optics, SCOTS provides a full-field measurement solution and comparable precision. Moreover, high dynamic range is another advantage in SCOTS. SCOTS test can easily accommodate to measure much steeper aspheric or free-form surfaces.

8848-16, Session 4

Application of time-invariant linear filter approximation to parameterization of one- and two-dimensional surface metrology with high-quality x-ray optics

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Numerical simulations of the performance of new x-ray beamlines and those under upgrade require sophisticated and reliable information about the expected surface slope and height distributions of prospective beamline optics before they are fabricated. Ideally, such information has to be based on metrology data obtained with existing optics, which are fabricated by the same vendor and technology, but generally, with different sizes, and slope and height rms variations. In a recent work [Opt. Eng. 51(4), 046501, 2012], it has been demonstrated that autoregressive moving average (ARMA) modeling of one-dimensional (1D) slope measurements with x-ray mirrors allows a high degree of confidence when fitting the metrology data with a limited number of parameters. With the parameters of the ARMA model, the surface slope profile of an optic with the newly desired specification can reliably be forecast. Here, we investigate the time-invariant linear filter (TLF) approach to optimally parameterize surface metrology of high quality x-ray optics thought of as a stationary uniform random process. We show that the TLF approximation has all advantages of one-sided AR and ARMA modeling, but it additionally gains in terms of fewer filter parameters and better spectral accuracy. Moreover, the suggested TLF approach can be directly generalized to 2D random fields. This work is supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

8848-17, Session 4

Correlation analysis of systematic errors in surface metrology with a slope profiler

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We describe, and present the mathematical foundation for, a novel method for the elicitation and suppression of contributions to systematic errors of surface slope profiler metrology. The method consists of the randomization of the systematic error by the averaging of multiple measurements, specially arranged to mutually anti-correlate. We also discuss the possibility to apply correlation analysis to the entire residual surface slope distribution in order to find anti-correlation parameters of the distribution. In this case, repeated measurements with the corresponding change of the experimental arrangement (position of the surface and/or its overall tilt) can be used to identify the origin of the observed anti-correlation features by analyzing the difference between the measurements. If the corresponding minimum of the auto-correlation function is due to a systematic error, averaging over the repeated measurements will provide an efficient suppression of the systematic error. If the observed anti-correlation properties are due to the polishing process, and therefore belong to the surface itself, we suggest that the possibility of re-polishing the surface based on the correlation analysis be considered. Throughout the present work we have discussed correlation analysis of surface slope metrology data. However, a similar consideration can be applied to surface topography in the height domain measured with other metrology instrumentation, for example: interferometers and interferometric microscopes. This work is supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

8848-18, Session 4

Surface metrology of off-axis paraboloids with a Zygo phase-measuring interferometer

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Increased brightness of updated 3rd generation synchrotron sources and FELs leading to smaller focused spots of x-rays has led optical designers to consider more and different methods of manufacture, and more and different figures for optical surfaces [Opt. Express. 17(20), 18271-18278, 2009]. The desire to achieve higher resolving powers for Resonant Inelastic X-ray Scattering (RIXS) also drives the interest in shapes which can focus to a point in monochromator designs. As a run up to potential future requirements in soft x-ray optical metrology, we investigate here the surface quality of off-axis paraboloids fabricated by diamond-turning. A novel method to measure off-axis parabolic optics is based on using gold microspheres as a diffraction limited back reflector in a double-bounce auto collimating geometry [SPIE Proc. 7102, 71020X (2008)]. We also discuss two other minor modifications to this experimental approach and compare them with the one using a diffraction limited ball to measure off-axis parabolic optics. Such methods may be extended, we propose, to ellipsoidally figured optics using converging rather than parallel light emerging from the interferometer.

8848-19, Session 4

Status of multi-beam long trace-profiler development

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The multi-beam long trace profiler (MB-LTP) is under development at NASA's Marshall Space Flight Center. The traditional LTPs scans the surface under the test by a single laser beam directly measuring the surface figure slope errors. While capable of exceptional surface slope accuracy, the LTP single beam scanning has slow measuring speed. Metrology efficiency can be increased by replacing the single laser beam with multiple beams that can scan a section of the test surface at a single instance. The increase in speed with such a system would be almost proportional to the number of laser beams. The progress for a multi-beam long trace profiler development will be presented.

8848-20, Session 5

Multilayer-based solutions for Extreme UV light with enhanced spectral purity

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We report on the development of multilayer based solutions to enhance the spectral purity of EUV light generated by plasma-based sources. These multilayer systems simultaneously reflect EUV radiation and suppress infrared (IR), e.g. scattered CO_2 laser radiation of the laser-produced plasma EUV sources. Two possible solutions are compared.

The first solution is the hybrid mirror that acts as an efficient Mo/Si Bragg reflector for EUV radiation at a given wavelength and simultaneously possesses spectral-selective suppression of the specular reflectance for unwanted infrared (IR) radiation due to the grating phase-shift resonance. Suppression of 70x factor is demonstrated for specular reflectance of IR radiation together with 61% EUV peak reflectance at 13.5 nm.

The second solution consists of an IR-transparent B_4C/Si multilayer stack which is used both as EUV-reflective coating and as a phase shift layer of the resonant IR antireflective (AR) coating. Suppression of more than two orders of magnitude at the target wavelength is demonstrated. The currently achieved EUV peak reflectance is about 45% at 13.5 nm.

8848-21, Session 5

Suppression of long wavelength reflection from Extreme-UV multilayer optics

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Plasma based radiation sources optimized to emit 13.5 nm Extreme UV radiation also produce a significant amount of light at longer wavelengths. This so called out-of-band (OOB) radiation is detrimental for the imaging capabilities of an EUV lithographic imaging system, in particularly the deep ultraviolet (DUV) and ultraviolet (UV) parts of the light (λ=100-400 nm).

To suppress these wavelengths, while maintaining the high efficiency of the mirror for EUV, several methods have been developed, including phase-shift gratings (PsG) and spectral-purity-enhancing (SPE) layers. PsGs use the diffraction property of a quarter-wavelength high multilayer grating to filter out the DUV/UV light, while the SPE layer works as an anti-reflection coating. Both methods have achieved a suppression factor of 10~30 around the target wavelength. To estimate the integral suppression of DUV/UV dose and the spectral characteristics in a real system, a typical laser produced plasma (LPP) source emission spectrum was included in the analysis. Different structures were optimized to obtain the highest integral suppression of the DUV/UV dose and these results are presented.

8848-22, Session 5

Reflectance of multilayer coatings for the lithography generation beyond EUVL

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Lithography based at 6.x nm wavelength is considered to be a potential extension of the current 13.5 nm EUV lithography.

On its development path it will meet significant challenges such as availability of a suitable source, resist, mask, and multilayer optics.

The topic of this paper is the possible improvement of La/B- based multilayers for the 6.5 to 7.0 nm wavelength range. The requirements for the multilayers are challenging: the current best achieved reflectivity ~ 50 % is significantly lower than desired ~ 70+ %.

Nitridation of La partly suppresses material inter-diffusion, resulting in 47% reflectance at normal incidence for LaN/B_4C multilayers at 6.6 nm, without any deposition process optimization. At off-normal angle experiments the multilayers with a larger bi-layer thickness show a reflectivity of 70% at 6.6 nm because of low influence of the interfaces on the reflectance. This value is close to the theoretical maximum.

The following possibilities to improve the normal incidence reflectance are identified and include:

- optimization of the nitridation of La,
- reduction of the interface roughness
- replacement of B_4C with B.

The results will be discussed.

8848-23, Session 5

Tackling the demands from new x-ray sources types with tailored multilayer optics

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Multilayer mirrors are used for increasing numbers of X-ray applications. While most multilayers in laboratory instruments are designed for common tube anode materials (Cu, Mo, Rh, Ag) and the respective characteristic fluorescence line energies, the development of new sources (such as liquid metal jet or laser plasmas) or special applications at synchrotrons and free electron lasers (with polarized radiation or photon energies in the range of few hundred eV) leads to a demand for tuned multilayer mirrors for those fields. We will present a number of special multilayers designed, fabricated and tested in state-of-the-art research, for example:

1) Polarization experiments require a grazing incidence angle of ~45°, much larger than the angle of total external reflection or typical multilayer mirror grazing angles. Thus, a multilayer with hundreds of extremely precise layers having thicknesses of only few Angströms is necessary. For synchrotron polarization experiments such mirrors were successfully produced and tested at wavelength.

2) Around the world numerous new X-ray sources in the soft X-ray range (such as free electron lasers or laser pulsed plasma sources) have started operation recently and for many applications monochromatizing optics such as multilayers are needed. Apart from the production, simulation and testing of these optics especially in the soft X-ray range below 100 eV is challenging due to missing optical constants and reliable calibrated sources, respectively. We simulated, manufactured and characterized multilayers in this range successfully using LPP and synchrotron sources at different laboratories. The measurements showed good agreement with theory.

8848-24, Session 6

Fabrication of x-ray gratings by direct-write maskless lithography

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Fabrication of diffraction grating for x-rays is a very challenging problem due to the exacting requirements of surface quality and groove profile. Traditional fabrication techniques have significant limitations and do not cover all necessary requirements. For example, classical holographic recording is limited in the type of groove patterns that can be produced. This is particularly important in the design of wide aperture high resolution spectrometers, where aberration correction using complex groove patterns is necessary. Traditional interference lithography and ruling methods are also limited in their ability to produce shallow blazed gratings with maximal efficiency. Here we will show how two new technologies are having an impact in this area and potentially will revolutionize grating performance. We are pioneering the use of direct-write mask-less lithography to make grating patterns of arbitrary complexity, together with the use of anisotropic etching of silicon to produce near atomically perfect groove shapes.

In this work we report on the first results from our direct-write mask-less approach, including quality assessment of the patterns using interferometric techniques, as well as new results on shallow blaze angle anisotropically etched silicon grating. This work was supported by the US Department of Energy under contract number DE-AC02-05CH11231.

8848-25, Session 6

Development of dispersive x-ray spectrometers and applications at SACLA

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For spectroscopic applications with XFEL light, we have developed two types of dispersive x-ray spectrometers for on-axis and emission geometries.

The on-axis spectrometer consists of an elliptical mirror, a flat analyzer crystal and a two-dimensional detector. We measured spikes of XFEL spectrum with resolution of 14 meV and determined the pulse duration with a help of an XFEL simulation. We have also applied this spectrometer to performing the absorption spectroscopy.

For dispersive emission spectroscopy, we propose a new scheme using a Johansson crystal and a two-dimensional detector. This device was successfully tested to measure Cu-Ka lines with XFEL. light.

8848-26, Session 6

Damage characteristics of platinum/carbon multilayers under focused x-ray free-electron laser irradiation

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X-ray free-electron lasers (XFELs) can now be used to produce intense femtosecond pulses in the hard X-ray region. The use of these X-ray sources in conjunction with analysis methods has unique advantages, and their applications in exploring new frontiers in science may be possible by using focusing optics. Sub-100 nm focusing under the diffraction-limited condition has already been achieved using total reflection mirrors. The use of X-ray mirrors for reducing the focal spot size requires a large grazing incidence angle in order to increase the numerical aperture. A multilayer mirror provides for a sufficiently large grazing incidence angle to accommodate spot size reduction, which cannot be achieved using total reflection mirrors. In this study, we evaluated the irradiation damage caused to platinum/carbon multilayers induced by hard XFELs. Intense X-ray beams cause damage to multilayer structures. In order to evaluate breakdown thresholds of the multilayer, we compared between the X-ray reflectivities of pre-irradiation and post-irradiation of XFELs in the first-order Bragg peak. We used a focusing XFEL beam with a beam size of approximately 1 μm at the photon energy of 10 keV. The pulse energy was controlled with silicon attenuators of various thicknesses placed in front of the focusing mirror. A pulse energy ranging from 0.01 to 100 μJ was applied in this experiment. We confirmed that the actual condition used is sufficiently lower than the breakdown threshold of platinum/carbon multilayers.

8848-27, Session 6

Damage threshold investigation using grazing incidence irradiation by hard x-ray free electron laser

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Since the advent of the X-ray free electron laser (XFEL) facilities, intense ultra-shot pulse and fully transverse coherent X-rays have been available even in the hard X-ray region. Such intense X-rays possibly induce damage of optical elements, which can be a serious problem of degradation in beam quality. To investigate damage thresholds of optical elements, we used focusing XFEL beam that has sufficient power density for studying ablation phenomena.

Focusing beams were produced by a pair of elliptical mirrors arranged in Kirkpatrick-Baez geometry at the XFEL facility SACLA (SPring-8 Angstrom Compact free electron LAser) in Japan. The focusing beam size was approximately 1 µm at a photon energy of 10 keV. We designed and installed a test chamber for irradiation experiments, which is equipped precise scan stages for measuring the beam size by a knife edge scanning method, online microscopes, and a rotation stage for grazing incidence irradiation. Single and/or multiple focusing XFEL beams irradiated to test samples under grazing incident condition. The samples were metal coated wafer that used as X-ray mirror optics. The damage thresholds were evaluated by measuring surface morphologies and X-ray reflectivity.

We found that obtained damage thresholds under grazing incidence condition were several times larger than melting dose calculated under the volume considering X-ray penetration depth.

8848-28, Session 6

Process-induced inhomogeneities in higher asymmetry angle x-ray monochromators

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Performance of asymmetric inline Ge(220)-based V-shaped monochromators has been recently studied both in metrological and imaging applications for photon energies around 8 keV. Due to refraction effect a drop of the transmitted intensity was observed for higher asymmetry angles. Several ways of correcting this effect have been successfully applied. To study output beam inhomogeneities, imaging experiments were performed at ESRF using a Frelon X-ray camera. By tuning the photon energy of synchrotron radiation the incidence angle and thus the asymmetry angle were changed.

Surface undulations due to chemical polish have been shown to negatively influence monochromator performance close to critical angle of 0.6°. Growth striations in graded GeSi and slightly misoriented grains in single Cu crystal (perspective materials for high intensity monochromators) are clearly visible in X-ray topographs, which fact excludes them from imaging applications. Low dislocation density G, though applicable for monochromators, is not recommended for imaging, neither. Diffracted beam inhomogeneities in thermally tuned V-monochromator may worsen beam parameters even when using dislocation-free material.

Pronounced increase of coherence volume by asymmetric X-ray diffraction gives large sensitivity to phase contrast and process induced surface features are observed as wavefield distortions in interference fringes.

Technological processing of Ge surface by chemical and chemomechanical polishing (CMP) was studied by several techniques. It was shown that CMP produces better surface homogeneity than chemical polish. However, CMP is more difficult to be applied in V-channels. For comparison, measurements on surfaces processed by a mechanical single point diamond turning have shown to be a perspective technology.

8848-29, Session PWed

The structure of chalcogenide glass-like semiconductors As-Se-S and As-Se-Te doped by samarium

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It is known that there is correlation between physical properties and structure in the chalcogenide glass-like semiconductors (CGS). Changing the process of the sample fabrication, the chemical composition and also doping by impurities in the form of charged centers allows modifying the structure of the CGS materials which influence on their electronic and optoelectronic properties.

This work is devoted to study the structure of the materials As-Se-S and As-Se-Te containing an impurity of samarium (0.1; 0.5; 1; 2; 2.5; 5 at%) by application of X-ray diffraction method.

Broad maxima in the diffraction pattern of films with low concentration of samarium (0.5 at%), show their amorphous nature. Parameters of the first sharp diffraction peak (FSDP) are defined by the special program Evaluation.

An occurrence and a form of FSDP on intensity curves of X-ray diffraction connect with the existence of ordering in the scale of the average order. We calculated the scattering vector corresponding to the FSDP position. The value of “quasi-period” of the structure or the density fluctuations of atoms was estimated. Repeatable of the later in some areas of correlation may stipulate the FSDP appearance. The correlation length (the area size in which the periodicity of the atom fluctuation is remained) was also determined.

The CGS materials differ from the corresponding crystals by existence of free volumes being voids with small sizes (nanovoids). The void diameter and the characteristic distance corresponding to the interatomic correlations were determined according to the Elliot void-cluster model. It was shown that the parameters of the As-Se-S and As-Se-Te structures differ significantly each other. It was connected with the size difference and variety of the structural units.

It was shown that influence of impurity of samarium on structural ordering of As-Se-S and As-Se-Te happens at the level of an average order and possesses the difficult character. Low concentrations (up to 0.5 at%) of samarium atoms increases, and high ones reduces the degree of ordering of the indicated materials. Such behavior is explained by the activity of impurity atoms rare earth elements (Sm), the nature of their distribution inside the sample, the manifestation in the form of positive ions Sm+3 and the change in the concentration of charged intrinsic defects (D + and D-).

8848-30, Session PWed

Using organic slab to obtain x-ray tube spectra for quantitative analysis of x-ray fluorescence analysis

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X-ray tube spectra are obtained using Oroglas materials as scatterers. The measured spectra are corrected for detector efficiency and Compton effect. The relative intensities of the elements in alloys are measured and calculated. The consistency of the experimental results and the theoretical values confirmed the validity of the corrected spectra, indicating that the method introduced in this letter is a simple and valid way of obtaining the X-ray tube spectra for quantitative analysis of X-ray fluorescence analysis.

8848-31, Session PWed

Diffraction grating efficiency calculations using genetic algorithms

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A web-based graphical user interface (GUI) has been developed to allow soft x-ray diffraction grating efficiencies to be performed in a parallel fashion. The open source web server Apache Tomcat was used for this purpose on a Linux-based computer. The interface was written in the hypertext preprocessor PHP. The diffraction grating efficiencies were modeled using the Fortran computer source code (Gradif) purchased from M. Neviere, which uses a differential method for solution. The GUI essentially serves as a wrapper to generate the required diffraction grating parameter description from the user, which is fed as input to the Gradif code. The GUI manages the set of calculations requested, extracting and displaying through plots the computed diffraction grating efficiencies.

The interface was developed as a web-based application so that it could be used anywhere through a browser within the Canadian Light Source (CLS) community, which is limited only by the licensing of the Gradif source code. This avoids having to distribute source code or installation on a person's individual computer. Support for multi-threaded calculations has been implemented to parallelize the calculations. Two additional desktop computers (Linux-based), each supporting dual quad-core CPU's, were set up to do these parallel calculations, which are separate from the web server. The user interface is open-source.

Support for genetic algorithms was recently added in order to more efficiently search for the global diffraction grating efficiency optimum as a function of parameter space. Genetic algorithms are based on the processes of genetics and evolution.

8848-32, Session PWed

Multilevel stacked Fresnel zone plate for hard x-rays

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An alternative type of multilevel Fresnel zone plate called stacked multilevel FZP, consisting of stacked layers with bi-level zone profiles, by means of numerical simulation was considered. The interlayer gap width and radial displacement of layers at which focusing properties of the system are close to that of corresponding multilevel FZP, aren't significantly differ from those of bi-level stacked FZP's.

As in the case of stacked bi-level FZP, interference fringes formed behind the optical system can be used as a criterion for layers radial alignment. An alternative criterion based on 0-order diffraction power also is applicable.

The angular sensitivity of the device was observed, and it was shown that it still allows good quality imaging of objects larger than the FZP's diameter. As an example the imaging of a grid structure has been simulated.

Considered approach of FZP fabrication allows achieving focusing efficiency sufficiently higher than the theoretical limit of efficiency for bi-level FZP. At that the fabrication of device does not become significantly difficult since the layers still have bi-level profiles. Another advantage of considered scheme is that it decreases the optimal height of layer profiles 1.5 times which leads to sharper focusing.

8848-33, Session PWed

The Alba ray tracing code: ART

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The Alba ray tracing code (ART) is a suite of Matlab functions and graphical user interfaces for the ray tracing simulation of x-ray beamlines. ART is organized in different layers. The lower level is constituted by a core of functions for source simulation, ray tracing on basic optical elements - including mirrors, capillaries, crystals and gratings - and a set of functions for statistical analysis of the sets of rays. The core functions can be run independently, or be integrated in functional programs such as beamline design optimization scripts. Within our ray tracing code, they constitute the basic functions for the intermediate layer of ART, which consists in functions that combine several optical elements in a single object. A typical case is the monochromator, which combines different optical elements whose positions and orientations are determined by the tuned energy. Finally, the top layer of the suite is the graphical user interface, called Artiface, which allows the user to control the beamline parameters from a simple graphical panel. Its main feature is that the beamline configuration file is a Matlab function itself, in which the user can insert code. This is particularly useful to explore how misalignments or tolerances affect the performance of the beamline, as well as to test combined-motion alignment routines. Other tools are included, such as a program to use measured slope errors, and to generate artificial slope errors starting from power spectral density distributions of real mirrors. ART also includes a grating efficiency package and a power distribution propagation calculator. Other generic characteristics of ART include the accumulation of rays to improve statistics without memory limitations, and providing normalized values of flux in physically meaningful units. The core functions to transform ART into a wave propagation code are currently under development.

8848-34, Session PWed

Error compensation for the calibration of mechanical mirror benders

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The use of linear methods to obtain both the error surface and the instrument error from redundant-independent datasets has been proposed to improve the accuracy of angle measuring scanning devices such as the long trace profilometer (LTP) or the nanometer optical measuring machine (NOM). The required redundant datasets of the surface are obtained by measuring the mirror several times, with a different pitch orientation with respect to the probe beam every time. The method allows obtaining both the slope profile of the surface under test and the linearity error of the measuring instrument.

In this work we propose to extend the method to measurements obtained during the calibration of a mechanical bender. In this case one obtains the required data redundancy from the measurements obtained

at the different bending conditions of the system. For all the bending conditions, the polishing slope error remains invariant, and the only difference between the different measurements is given by the elastic deformation of the substrate, which depends on two parameters only. In addition, such deformation is very reliably modeled by the elastic beam theory, for the most usual ranges of curvature. The proposed method allows determining an error-free measure of the slope error, the curvature and the cubic component of the mirror, as well as the instrument error. The description of the method, as well as simulations and practical works are presented.

8848-35, Session PWed

Modulation of intensity in defocused beams

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Many X-ray techniques require variable size photon beam on the sample or on the detector. The easiest way to achieve variable spot size is to defocus the beam, typically by changing the bending of the focusing mirrors. Nevertheless, defocusing has the problem that the beam profile is heavily modulated by striations caused by the surface error of the focusing optics. To our knowledge, a relationship between these modulations of the beam and the spatial frequency of the surface error that originates them has not been properly established. In this work we show that beam modulation at a given measurement plane has a nonlinear dependence on the slope profile of the mirror, and on the positions of the focal plane and the measurement plane. The modulation is, in addition, convoluted with the stenopeic image of the source, which behaves as a low-pass filter smoothing out high spatial frequency striations. From the derived relationships it follows that the relative contributions to beam striations of slope error lower and higher spatial frequencies vary depending on how far away the measurement plane is from the focal one. Finally, we explore the relationship between the amplitude of the striations and the power spectral density of the slope errors.

8848-36, Session PWed

Optimization of the soft x-ray transmission microscopy beamline at the ALBA light source

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Mistral is the soft X-ray full field microscopy beamline at the ALBA light source. The beamline is fed by a bending magnet, and it is designed to have large source acceptance and to provide constant angular magnification at the exit slit for photon energies between 270 and 2600 eV. The monochromator is a variation of the Petersen plane grating monochromator in which a variable line spacing grating (VLS) is used to maintain the focus fixed for all energies at the exit slit plane, as well as to cancel higher order aberrations. In order to obtain the desired acceptance and spectral resolution, very large optical surfaces, up to 1.2 m long, and very short distances between them were required. A consequence of this is that the spectral resolution of the beamline is very sensitive to misalignments and to manufacturing tolerances of its optical elements such as the radii of curvature of the optical surfaces, and especially the VLS parameters of the gratings. Another constraint is given by the requirement of the x-ray microscope to have the beam focused both vertically and horizontally onto the exit slit.

In this work we present the alignment strategy we followed during the commissioning, which we used to compensate for the tolerance errors of the optical elements in order to achieve the required spectral resolution, and to preserve both vertical and horizontal focus at the same plane. We also give details on how mechanical stress torsion was diagnosed on one of the gratings, and on how the energy calibration of the monochromator was performed. Finally we report on how the beamline is capable of compensating drifts of the source position preserving the beam conditions at the exit slit and on the microscope.

8848-37, Session PWed

Development of an objective flat-field spectrograph for electron microscopic soft x-ray emission spectrometry in 50-4000 eV

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We have developed an objective soft x-ray flat-field spectrograph to be able to attach to electron microscopes (EMs). This spectrograph has two attractive features. One is that it is designed to cover a wide energy range of 50-4000 eV by using four varied-line-spacing holographic gratings (VLSHGs) optimized for 50-200 eV, 155-350 eV, 300-2200 eV, and 2000-4000 eV. The gratings dedicated for the respective energy ranges can be accommodated in the single spectrograph. This advantage comes from that the positions of the source points and image planes are assumed as the common parameters in the design of the all gratings. Therefore, it allows us to easily change the energy range by only choosing an appropriate grating and its position. The other is the application of a newly invented W/B4C multilayer coating. It has been adopted to the grating for the 2000-4000 eV range to overcome the considerable decrease of the diffraction efficiency in the energy range above ~2 keV. The novel coating allows us to enhance the diffraction efficiency up to a practical level, at least over 1%, at a constant incidence angle in the whole energy range. The multilayer structure is based on the same concept as hard x-ray supermirrors, but extremely simplified.

The details of the optical design of the spectrograph accommodating four VLSHGs, the conceptual design of the multilayer structure, the diffraction efficiencies and resolving power obtained experimentally as well as some emission spectra measured by the spectrographs attached to EMs will be presented in the conference.

8848-38, Session PWed

Investigation of high-thermal-contact-conductance in low-contact pressure for high-heat-load optical elements of synchrotron radiation

Tomoyuki Takeuchi, Masayuki Tanaka, Haruhiko Ohashi, Shunji Goto, Japan Synchrotron Radiation Research Institute (Japan)

Many high-heat-load components are cooled by water or liquid nitrogen under indirect configuration for synchrotron radiation beamlines. Thermal-contact-conductance (TCC) is crucial property for the design of indirect cooling components. TCC depends on contact material, contact pressure, and surface condition. Low contact pressure is needed to reduce strain on an optical element, resulting in small value of TCC. We are seeking a condition with interstitial material of a high TCC in low contact pressure region.

The TCC measurements were performed between copper rods with interstitial material under water cooling, in vacuum, and under low contact pressure of 0.1-1.0 MPa. Large variance of TCC was observed for a bare surface of copper due to surface oxidization. Although, nickel-plated copper showed stable TCC value, it was smaller than that of bare copper. We will show TCC results that will be applied for indirect-cooling crystal monochromators and mirrors.

8848-39, Session PWed

Engineering optical constants for broadband single layer anti-reflection coatings

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Single layer anti-reflection coatings are often assumed to be limited to minimize reflection in a narrow bandwidth around a specific wavelength. In this paper we show that there are in principle no fundamental restrictions for single layer anti-reflection coatings to exhibit broadband suppression. We present theoretically derived design rules for an anti-reflection coating for the spectral range of 100N400 nm, applied here on top of a molybdenum-silicon multilayer mirror as commonly used in extreme-ultraviolet lithography. The design rules for optimal suppression are found to be strongly dependent on the thickness and optical constants of the coating. As a proof of principle, thin films were deposited that exhibit optical constants close to the design rules for suppression around 300 nm.

In order to minimize EUV absorption losses, we used silicon based compounds which are relatively transparent to EUV radiation. SixCyNz layers were deposited by electron beam co-deposition of silicon and carbon, with N+ ion implantation during growth.

The thin films were analyzed with variable angle spectroscopic ellipsometry to characterize the optical constants. The results show that the optical constants of SixCyNz films can be engineered to match those specified by the design rules. This work illustrates that a single layer anti-reflection coating can be used to achieve broadband suppression using appropriately tailored optical constants.

8848-40, Session PWed

Recent performance of the APS optical slope measuring system

Jun Qian, Lahsen Assoufid, Joseph Sullivan, Argonne National Lab. (United States)

Abstract: An optical slope measuring system (OSMS) at the Advanced Photon Source of the Argonne National Laboratory was first reported in 2012 [1]. This system is equipped with a precision autocollimator and a very accurate mirror-based pentaprism on a scanning stage and kept in an environment-controlled enclosure. This system has the capability for measuring precision X-ray optics with sub-microradian rms slope errors, which has been verified via a number of measurements with high quality mirrors. In this paper, we gave recent performance of the system, including stability, repeatability and reliability, after more precise optical alignment and better temperature control.

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Conference 8849: X-Ray Lasers and Coherent X-Ray Sources: Development and Applications X

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8849-1, Session 1

Double-stage soft x-ray laser pumped by multiple pulses applied in grazing incidence *(Invited Paper)*

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X-ray laser (XRL) research activities at PHELIX / GSI are dedicated to establish a reliable, fully characterized nickel-like plasma - XRL source for application, in particular for performing spectroscopy experiments on highly charged heavy-ions stored in the Experimental Storage Ring (ESR) of the GSI accelerator structure and later on at the HESR High-Energy Storage Ring at FAIR[1]. Plasma XRL sources will allow the direct excitation of 1S – 2P1/2 transitions of a large number of Lithium like ions, including also radioactive isotopes, for precision studies of high-field physics.

We report here on results of laser seeding in a two-stage plasma XRL scheme. The two targets were pumped using the double-pulse grazing incidence pumping technique, which includes travelling wave excitation for both the seed- and the amplifier-target[2]. In addition, another pumping scheme relying on a third pulse has been studied. Seeded x-ray laser operation has been demonstrated in both schemes, resulting in x-ray laser pulses with a divergence of 2 mrad x 2 mrad. The peak brilliance of the amplified x-ray laser of 4x1023 photons /s /mm^2 /mrad^2 in 5x10-5 relative bandwidth was more than two orders of magnitude larger compared to the original seed pulses. The presented experimental concept provides an alternative to the currently more common approach to use high-order harmonic pulses as a seed source, with a perspective [3] leading towards even much higher brilliance.

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8849-2, Session 1

Sub-10-nm Ni-like soft-x-ray lasers

Juerg E. Balmer, Fei Jia, Felix Staub, Univ. Bern (Switzerland)

We report on recent progress achieved in x-ray laser research at the Institute of Applied Physics of the University of Bern. Using the existing 10-TW Nd:glass CPA (chirped-pulse amplification) laser system in the grazing-incidence pumping (GRIP) scheme, saturated or near-saturated soft-x-ray lasing has been obtained on the 4d - 4p, J = 0-1 lines of barium (Ba, Z = 56), lanthanum (La, Z = 57), and samarium (Sm, Z = 62) at wavelengths down to 7.36 nm, with weak lasing observed at 6.85 nm. This was achieved with main pulse energies of ~10 J and a pulse duration of 1.5 ps. Crucial to these results was the introduction of a second, relatively intense (16%) prepulse ~30 ps before the main pulse, in addition to the 8% prepulse incident on target several nanoseconds before the main pulse. A small-signal gain coefficient of ~30 cm^-1 and a gain-length product of ~16 at saturation have been measured in the case of the 9.2-nm Ba laser. Crucial to these results was the introduction of a second, relatively intense (~15%) prepulse less than ~50 ps before the main pulse, in addition to the 2.8% prepulse that irradiated the target ~3 ns earlier. Traveling-wave excitation was used throughout.

8849-3, Session 1

Development and applications of X-ray lasers at PALS Centre

Michaela Kozlová, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The results of development and aplications of the X-ray sources at PALS Center will be presented. Currently the iodine system and the Ti:Sapphire system are operating at the PALS Center as driving lasers for generation of secondary sources. The iodine system with net energy of 1kJ is used for QSS lasing schemas. The most robust and most energetic QSS schema with this driver is Ne-like Zn X-ray laser, which is working here as standard user beamline for diverse applications. The second system with high rep rate is Ti: Sapphire laser chain with peak power 20TW. This laser system is used for generation HHG and GRIP schema.

8849-30, Session 1

Maxwell-Bloch modelisation of the amplification of a double seed pulse with variable delay

Philippe Zeitoun, Ecole Nationale Supérieure de Techniques Avancées (France); Thi Thu Thuy Le, Eduardo Oliva, Univ. Paris-Sud 11 (France); Li Lu, Ecole Nationale Supérieure de Techniques Avancées (France); David Ros, Univ. Paris-Sud 11 (France); Jorge J. Rocca, Colorado State Univ. (United States)

Ultra-fast and ultra-intense soft x-ray sources, like high harmonic generation and free-electron lasers, opened new avenues for applications in solid-state physics, biology, plasma physics etc. Most recent applications required x-ray pulses with high degree of spatial coherence, good wave front and duration below 100 fs. Plasma-based soft x-ray lasers have the potentiality to complement soft x-ray free-electron lasers by delivering ultra-intense and energetic beams to users. In this perspective, the most advanced concept is based on the transposition of Chirped Pulse Amplification in X-rays [Oliva et al, Nat. Phot, 2012]. This technics relies on the fast recovery of gain after amplification of ultra-fast seed. As a first step, we numerically study the amplification of two seed pulses with variable delay between them. Such double pulse has interest for pump-probe experiments. Using 1D time-dependant Maxwell-Bloch model that includes amplification of spontaneous emission, we modelled the temporal variation of the intensity of the two seed pulses for various conditions. We consider neonlike zinc plasma amplifying high harmonics at 21.2 nm. We observed the interaction of the two pulses for delays below 2 ps.

8849-5, Session 2

Bright ultrahigh harmonic generation in the keV x-ray regime using tabletop mid-IR lasers *(Invited Paper)*

Tenio Popmintchev, Ming-Chang Chen, Dimitar Popmintchev, JILA (United States); Skirmantas Alisauskas, Giedrius Andriukaitis, Audrius Pugzlys, Andrius Baltuska, Technische Univ. Wien (Austria); Bonggu Shim, Alexander L. Gaeta, Cornell Univ. (United States); Carlos Hernandez-Garcia, Luis Plaja, Univ. de Salamanca (Spain); Margaret M. Murnane, Henry C. Kapteyn, JILA (United States)

We demonstrate the most extreme phase-matched nonlinear upconversion process to date, coherently combining over 5001 mid-infrared femtosecond laser photons to generate bright ultra high-order harmonics spanning the electromagnetic spectrum from the UV to above 1.6 keV. In a remarkably favorable convergence of nonlinear optical phenomena, the multi-atmosphere gas pressures that enable efficient X-ray generation also self-confines the laser beam, further enhancing the X-ray yield. This realizes the first coherent version of the Roentgen X-ray tube in the soft X-ray region of the spectrum on a tabletop. We also present a generalized picture of phase matching of high harmonic generation (HHG) that combines microscopic quantum physics with macroscopic extreme nonlinear optics. Counterintuitively, to generate the brightest harmonics, the order of the nonlinearity must dramatically increase from ~11 in the VUV, to >101 in the EUV, to >5001 in the keV X-ray region. The phase-matched emission evolves from a single harmonic in the VUV, to a broad X-ray supercontinuum spanning thousands of harmonics in the soft X-ray region that in theory can support single cycle X-ray pulses as short as 2.5 attoseconds. Finally, when longer-wavelength driving lasers are used, the phase-matched ultrahigh harmonic generation is scalable to even sub-attosecond (zeptosecond) time scales. These unique ultrafast HHG X-rays of full spatial and temporal coherence can capture the fastest motions of charges, spins, phonons and photons in molecules and materials in real time, as well as enables imaging near the wavelength limit.

Reference: Popmintchev et al, Science 336, 1287 (2012).

8849-6, Session 2

Generation of a beat-wave pulse train for quasi-phase-matched high-harmonic generation

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For efficient high-harmonic generation at short wavelengths, a beat-wave pulse train is generated from a two-color Ti:sapphire amplifier system. By using such pulse train to collide with the main driving pulse in the interacting media, quasi-phase matching can be achieved. The 66-fs pulse separation matches to a quasi-phase-matching zone length of 4.9 µm, which corresponds to a dephasing length for 3-nm harmonic generation under 1.0x10^18 cm^N3 plasma density.

The two-color amplifier system is a branch of the 100-TW Ti:sapphire laser system we built at National Central University. We split a 1-mJ pulse from the main amplifier chain as its seed pulse. It is compressed and focused into a krypton-filled tube for supercontinuum generation. The supercontinuum spectrum is shaped by an acousto-optic programmable dispersive filter into a twin-peak structure, and then seed into a two-stage Ti:sapphire amplifier chain. The final output spectrum has equal intensity and bandwidth of its 877-nm peak and 907-nm peak.

The two-color output wave is compressed by a grating compressor. As a result of that the two frequency components are spatially separated on the roof mirror, we use individual roof mirror for each component to adjust their relative delay. For demonstration, we compress the two-color wave to 600-fs duration. A train of about 10 pulses with 66-fs separation is observed by general cross-correlation measurement. The total energy of the two-color beat wave is 100 mJ. It can support an envelope duration longer than 100 ps, corresponds to a number of quasi-phase-matching zones more than 1000.

8849-7, Session 2

Transmission imaging of sodium in the vacuum ultra-violet spectral range: new application for an intense VUV source

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Although the metallic sodium was proposed as a transparent material in the vacuum ultra-violet (VUV) spectral range in 1930s (1) and in 1960s, (2) the extinction coefficient was measured with use of only a sub-?m thick sodium foil on a substrate. However no clear transmission has been demonstrated. In this paper we describe the direct measurement of actual transmittance of a sodium sample with thickness of a 1~3 mm instead of sub-m layers in a spectral range longer than 115 nm which corresponds to the shortest transmission wavelength of magnesium fluoride (MgF2) windows, resulting in, for example, 30 % transmittance of a 3 mm thick solid sodium sample including MgF2 windows and the reflection losses at the wavelength of 120 nm with very weak temperature dependence up to 120 degrees centigrade which is beyond the melting point of 97 degrees. Based on the transmission measurements, we set up a simple transmission imaging configuration with a 2-mm thick sodium sample, resulting in clear images composed of 100 m diameter tungsten bars recorded on a two dimensional Charge Coupled Device detector coupled with a phosphor plate and optical fibers. The result also opens a way to construct an optical imaging device for objects inside or through a solid or a liquid sodium medium with thickness of several cm. We believe that the present results show a real demonstration of the transparent sodium in the VUV spectral range proposed firstly by Wood. According to the present extinction coefficient coupled with layer to layer reflectivity, we can make a continuous real time transmission imaging experiment for a few-cm thick liquid sodium sample if we use proper optical setup including an intense VUV source. Such an experiment opens up a way to design and construction of a visualization device for transmitted images through or inside a sodium medium.

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8849-8, Session 2

On-axis and off-axis high-order harmonics generation by relativistic laser in gas jet target *(Invited Paper)*

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(Japan); Paul R. Bolton, Sergei Bulanov, Kiminori Kondo, Japan Atomic Energy Agency (Japan)

We have recently discovered a new regime of high-order harmonic generation [Phys. Rev. Lett. 108, 135004 (2012)] by multi-TW femtosecond lasers focused to gas jet targets, where comb-like spectra with hundreds of harmonic orders, reaching the photon energy of 500 eV, including the 'water window' spectral range, were generated by either linearly or circularly polarized pulses. In this presentation we describe the results of new experiments with the J-KAREN laser in KPSI, JAEA, namely (i) the discovery of a strong off-axis XUV high-order harmonics emission, (ii) the detailed study of the high-resolution on-axis harmonics spectra, and (iii) the measurements of the harmonics source size and angular divergence which allow more accurate estimate of the peak spectral brightness, much more favorable compared to the previous conservative estimates.

8849-9, Session 3

The optical design of the soft x-ray self seeding at LCLS

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After the successful demonstration of the hard X-ray self-seeding at LCLS (Nature Photonic 6(10) 693 (2012)), an effort to build a system for working in the soft X-ray region is ongoing. The idea for self-seeding in the soft X-ray region by using a grating monochromator was first proposed by Feldhaus et. Al (Opt. Comm., 140, 341 (1997)). The concept places a grating monochromator in middle of the undulators and selects a narrow bandwidth "seed" from the SASE beam produced by the upstream section of undulators, which is then amplified to saturation in the downstream section of the undulators. The seeded FEL beam will have a narrower bandwidth approaching the transform limit. The challenge is to accommodate a monochromator and refocusing system as well as the electron beam magnetic chicane into a very limited space. The LCLS prototype replaces only a single undulator section of ~ 4 m. A general description of the Soft X-ray Self seeding project and the expected FEL performances are described elsewhere (proceeding of the FEL 2012 conference). Here we present the detailed optical design solution, consisting of a fixed incidence angle toroidal blazed grating with variable groove density, a rotating plane mirror (the only required motion for tuning the energy) to redirect the selected monochromatic beam onto an exit slit, and two more mirrors, one sphere and one flat, to focus and overlap the 'seed' onto the electron beam in the downstream undulators. The performance, ablation issues, metrology and alignment will also be discussed.

8849-11, Session 3

Imaging of fine structures of cellular organelles in hydrated biological cells by a soft x-ray microscope combined with a fluorescence microscope

Masataka Kado, Maki Kishimoto, Japan Atomic Energy Agency (Japan); Satoshi Tamotsu, Keiko Yasuda, Masato Aoyama, Nara Women's Univ. (Japan); Kunio Shinohara, Japan Atomic Energy Agency (Japan)

Soft x-ray microscope is very powerful tool to observe cellular organelles of hydrated biological cells and many works have demonstrated imaging of inner structures of the cells. However the inner structures are very complicated and it is difficult to identify the organelles from the image obtained with the soft x-ray microscope by itself. We have proposed to use a fluorescence microscope to identify the cellular organelles in the images obtained with the soft x-ray microscope observing the same cells with both microscopes. We have developed a special specimen holder designed to be optimized for the application to both microscopes so that the cells in the specimen holder can be observed by the both microscopes. The cells were cultivated directly onto the PMMA photo resists and stained in advance with several fluorescent dyes such as Mito-tracker, Phalloidin, and DAPI to image mitochondria, actin filament, and chromatin, respectively. Right after taking many fluorescence images of cellular organelles the cells were exposed to the flash soft x rays radiated from thin foiled gold plasmas produced by a 20 J, 600 ps pulsed laser. The obtained soft x-ray images and fluorescence images of the cells were directly compared and each of the cellular organelles such as mitochondria, actin filaments, and chromosomes in the soft x-ray images was clearly identified. Since the soft x-ray microscope has higher spatial resolution than that of the fluorescence microscope, fine structures of the cellular organelles in the hydrated biological cells were observed for the first time.

8849-12, Session 3

Corrosion-resistant Mg/SiC multilayer coatings for EUV laser sources in the 25-80 nm wavelength region *(Invited Paper)*

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The 25-80 nm wavelength region is part of the operational range of extreme ultraviolet (EUV) free-electron laser and tabletop laser sources, with applications in plasma physics, materials characterization, photochemistry, nano-patterning, and microscopy. These applications require multilayer-coated optics as collector and imaging elements. Mg/SiC possesses a unique combination of favorable reflective properties, unmatched by any other candidate multilayer coating in the 25-80 nm region: consistently high reflectance, near-zero film stress, good spectral selectivity and thermal stability up to 350? C. However, Mg/SiC suffers from Mg-related corrosion, an insidious and unpredictable problem which completely degrades reflectance and has prevented Mg/SiC from being used in applications that require long lifetime stability. We have elucidated the origins and mechanisms of corrosion propagation within Mg/SiC multilayers. Based on our findings, we have demonstrated an efficient and simple-to-implement corrosion barrier for Mg/SiC multilayers. The barrier consists of nanometer-scale Mg and Al layers that intermix spontaneously to form a partially amorphous Al-Mg layer and is shown to dramatically reduce corrosion while maintaining the unique combination of favorable Mg/SiC reflective properties. We have demonstrated experimentally a variety of concepts for corrosion-resistant Mg/SiC multilayers which achieve high reflectance in up to three narrow bands simultaneously, in the 25-80 nm region. We have also measured and modeled the in-band and out-of-band response of these multilayers in the 11-200 nm wavelength range.

8849-27, Session 3

Femtosecond x-ray pulse temporal characterization in free-electron lasers *(Invited Paper)*

Christopher Behrens, Deutsches Elektronen-Synchrotron (Germany) and SLAC National Accelerator Lab. (United States)

The ability to temporally characterize x-ray pulses from free-electron lasers (FELs) will underpin their exploitation in experiments ranging from single-molecule imaging to extreme timescale x-ray science. This issue is especially acute when confronted with the characteristics of current generation x-ray FELs, as most parameters fluctuate strongly from pulse to pulse. Here, we review recent advances in the temporal characterization of x-ray pulses at FELs, with the emphasis on techniques of femtosecond resolution and single-shot capability. Measurements in the soft and hard x-ray regime of current generation x-ray FELs will be discussed.

8849-13, Session 4

Observation of the nano-scale surface dynamics of femtosecond laser ablation by time-resolved soft x-ray imaging technique *(Invited Paper)*

Masaharu Nishikino, Noboru Hasegawa, Japan Atomic Energy Agency (Japan); Takuro Tomita, Univ. of Tokushima (Japan); Yasuo Minami, Ryota Takei, Motoyoshi Baba, The Univ. of Tokyo (Japan); Takashi Eyama, Takayoshi Syodai, Univ. of Tokushima (Japan); Tetsuya Kawachi, Mitsuru Yamagiwa, Japan Atomic Energy Agency (Japan); Tohru Suemoto, The Univ. of Tokyo (Japan)

The dynamical processes of the femosecond laser-induced surface modifications come to attract much attention for the micro processing. However, it is difficult to observe the femtosecond laser ablation dynamics, because of non-repetitive, irreversible and rapidly changing phenomena in a small characteristic size. Thus, the details of femtosecond laser ablation process have not been understood well. The measurement technique with the sufficient temporal and spatial resolution is necessary for the better understanding of the femtosecond laser ablation. In this study, we have developed the pump and probe interferometer and reflective imaging technique of the metal surfaces during the femtosecond laser ablation by using the laser-driven soft x-ray laser at the wavelength of 13.9 nm. The pumping laser used for the ablation was a Ti: Sapphire laser pulse with the duration of 80 fs pulse at a central wavelength of 795 nm, and had a gaussian spatial profile. By using the x-ray imaging technique, the time resolved image of nano-scaled ablation dynamics of the platinum was obtained. At the timing of 36 ps after the femtosecond laser irradiation, the maximum surface expansion and expansion speed were measured to be about 60 nm and 1700 m/s, respectively. We have compared the plasma expansion measured by the x-ray interferometer with the ablated hole measured by the atomic force microscopy, and discussed the fluence dependence of the femtosecond laser ablation. These results lead to better understanding of the initial process of the laser ablation dynamics.

8849-14, Session 4

Nano-meter scale modifications on material surfaces induced by soft x-ray laser pulse irradiations

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To study the interactions between soft x-ray laser (SXRL) beam and material surfaces, we irradiated the SXRL beam pulses having a wavelength of 13 nm and duration of 7 ps to aluminum (Al), gold (Au), copper (Cu), and silicon (Si) surfaces. Following irradiation, the surfaces were observed using a scanning electron microscope and an atomic force microscope. With single pulse irradiation, the formation of conical structures was observed on the Al surface, and ripple-like structures were formed on the Au and Cu surfaces. The conical structures on Al surface were destroyed under the multiple SXRL pulse exposures, but it was confirmed that the development of modified structures was observed after multiple pulse exposures on the Au and Cu surfaces. On the Si surface, deep holes that seemed to be melted structures induced by the accumulation of multiple pulses of irradiations were found. Therefore, it was concluded that SXRL beam irradiation of various material surfaces causes different types of surface modifications, and the changes in the surface behaviors are attributed to the differences in the elemental properties, such as the melting points and the attenuation length of x-ray photons.

8849-15, Session 4

Nanoscale 3D chemical contrast imaging by soft x-ray laser ablation mass spectrometry

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Mass Spectrometry Imaging (MSI) has played an important role in the direct examination of the chemical composition of complex inorganic and organic samples. Typically a visible/ultraviolet laser is used to ablate the sample and create ions that when detected allow to identify molecular composition. We have pioneered the use of soft x-ray (SXR) lasers in the implementation of a novel laser ablation mass spectrometry (XLAMS) nanoprobe that can probe chemical composition from sample regions of a few atto-liters volume and with high sensitivity. The concept exploits: i) high focusability, ii) low penetration depth and iii) high photo-ionization efficiency of the 46.9 nm wavelength SXR laser light. In this work we demonstrate the capabilities of XLAMS to realize 2D and 3D chemical contrast imaging with ~140 nm lateral and ~50 nm depth resolution and high sensitivity. The high lateral and depth resolution and high sensitivity of XLAMS imaging method offer great potential for composition imaging of nanofilms and nanostructures and imaging the chemical distribution of dopants and trace elements.

8849-16, Session 4

Prospects of ultrafast x-ray absorption investigations using laboratory based sources

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Ultrafast X-ray absorption spectroscopy (UXAS) offers the opportunity to investigate function-structure relationships of complex organic molecules

or biological functional subunits without the need of crystallization. Of special interest from the viewpoint of structural biology are the spectral region of the so called water window (280.. 500 eV) and the region of K-edges of transition metals between 4 and 10 keV. It should be noted that the structural information gained from UXAS is complementary to the related data derived from time-resolved diffraction measurements. Regardless of successful application of time-resolved diffraction techniques to investigations of crystal dynamics using synchrotron and laboratory based sources [1] there are only very few examples for application of UXAS to revealing the structural dynamics in biomolecular systems. This is mainly caused by the lack of broadband ultrafast sources as well as of appropriate X-ray optics adopted to these sources. Due to the long-data-recording time in UXAS experiments the sample integrity is mainly determined by the average power of the pump pulse. Using a fixed energy of the pump pulse the latter one is determined by the repetition rate of the pump laser. In this paper we discuss the prospects of UXAS comparing fs laser plasma sources with different repetition rates together with tailor-made optics [2] based on highly annealed pyrolytic graphite (HAPG).

[1] Zamponi, F., et al. PNAS 2012. 109, 5207

[2] Legall, H., H. Stiel, et al. J. Appl. Cryst., 2009. 42

8849-17, Session 4

Experimental set-up for high-resolution x-ray spectroscopy of solid and liquid samples

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Here we present an experimental setup for high resolution X-ray spectroscopy of solid and liquid samples in the soft X-ray region. The setup consists of a multipurpose chamber, a high resolution grating spectrometer in grazing incident, a photodiode and a sample holder for both solid and liquid targets. The concaved curvaured grating has 2400 grooves/mm and a curvaure radius of 57860 mm covering a wide rage of energies, from soft X-rays up to a few keVs. The photodiode is placed wiht an angle of 90° in respect to the target and records the absorption in fluoresence yield. An advantage of the experimental setup is the target holder, which can povide solid or liquid samples. The liquid jet delivery system is capable of providing liquid jets with diameter from 5-100 micrometers. The liquid jet provides always fresh samples and therefore radiation damage can be prevented. The liquid environment is especially important for experiments with biological and chemical purpose. The samples are collected by a cooling finger immersed in liquid nitrogen. This setup is also be used for ultrafast pump/probe experiments.

8849-18, Session 5

Multi-tens of GW peak power plasma-based soft X-ray laser *(Invited Paper)*

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Ultra-intense X-ray sources have opened new avenues by creating new states of matter or probing and imaging living or inert matter. Free-electron lasers have a strong leadership by delivering pulses combining femtosecond duration and 10's of microJoules to milliJoule energy. However, these sources remain highly expensive limiting their number to a few worldwide. In parallel, laser-pumped soft X-ray lasers hold outstanding promises having demonstrated the most energetic monochromatic soft x-ray pulse and being intrinsically fully synchronized with any secondary source of the pump laser. Since the first successful demonstration of amplification of a high harmonic pulse in a plasma from gas in 2003 [1] and from solid in 2008 [2], we have developed an extensive numerical study.

2D hydrodynamic simulations showed that optimized Transient Collisional Excitation plasma amplifiers, may store up to 0.4 mJ in the population inversion. If carefully seeded, pulses of 80 fs and 20 μJ might be generated with table-top lasers (10J).

As the energy extracted is far from the milliJoule requirements of most exciting applications, we studied the seminal experiment of Ditmire et al [3] who seeded a plasma emitting milliJoules in the form of Amplified Spontaneous Emission (ASE).We retrieved and explained for the first time the experimental result (ASE 1,000 times stronger than amplified seed). We thus proposed and fully modeled the transposition of the so-called Chirped Pulse Amplification (CPA) in the soft X-ray range, showing that 6 mJ, 200 fs, fully coherent soft X-ray pulse is accessible with compact pump lasers [4].

8849-19, Session 5

Measurement of the gain dynamics in injection-seeded soft x-ray lasers

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The generation of intense pulses of coherent soft x-ray radiation is of great interest for applications in numerous fields. Injection-seed plasma amplifiers have been demonstrated to produce intense fully phase coherent soft x-ray pulses. Herein we report the measurement of the gain dynamics in a soft x-ray plasma amplifier seeded by high harmonic pulses. A sequence of two time-delayed spatially-overlapping high harmonic pulses was injected into a λ=18.9 nm Ni-like Mo plasma amplifier to measure the regeneration of the population inversion that follows the gain depletion caused by the amplification of the seed pulse. Collisional excitation is observed to re-establish in about ~ 1.5 ps the population inversion depleted during the amplification of the seed pulse. The measured gain-recovery time is compared to model simulations to gain insight on the population inversion mechanisms that create the transient gain in these amplifiers. This result indicates that an amplification scheme based on the continuous extraction of energy from a soft x-ray plasma-based amplifier by an stretched seed pulse has the potential to generate ultra-intense fully phase-coherent soft x-ray laser pulses.

8849-20, Session 5

Modeling and numerical simulations of seeded XUV lasers with the COLAX code: recent progress

Annie Klisnick, Andréa Le Marec, Univ. Paris-Sud 11 (France); Olivier Larroche, Commissariat à l'Énergie Atomique (France)

Seeding of plasma-based XUV lasers with a femtosecond coherent external pulse, such as high-order harmonic radiation, is a very promising technique to drive these lasers towards better beam quality and significantly enhanced peak power. Experimental progress toward these goals requires support from numerical simulations able to describe the

strongly non-linear regime of amplification induced by seeding in a high-gain, narrow-band amplifier. Such simulations are based on a Maxwell-Bloch description of the amplified field and atomic polarization. We describe recent studies performed with our recently upgraded COLAX code to investigate the coherence and temporal behaviour of the seeded XUV laser pulse.

8849-21, Session 5

Wavefront of seeded soft x-ray laser based on solid-plasma amplifier

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This experiment set out to determine the wavefront of seeded soft x-ray laser with solid-plasma amplifier. The 43rd harmonic signal from neon gas jet has been amplified by seeded to the molybdenum plasma. Hartmann wavefront senor with accuracy at λ/50 rms was employed to measure the wavefront of both high harmonics and amplified soft x-ray lasers. Significant improvement of wavefront after plasma amplifier (from HHG 0.51λ rms to seeding 0.23λ rms) has been observed in agreement with previous studies on gas ampifier. In addition, we measured the wave front for plasma lengths ranging from 2.5 to 5 mm and observed a net improvement for the longest plasmas. Optimization of wave front versus seeding time has been completed showing a slight influence of this parameter. For every condition, wave fronts have been decomposed on the first Zernike polynomials (up to coma at 0°) giving better insight on the spatial filtering achieved during amplification. Finally, soft x-ray source structures have been retrieved from the wave fronts and intensity maps.

8849-22, Session 5

High-average-power 100-Hz repetition rate table-top soft x-ray lasers *(Invited Paper)*

Jorge J. Rocca, Brendan A. Reagan, Keith Wernsing, Yong Wang, Liang Yin, Shoshun Wang, Mark Berrill, Mark R. Woolston, Alden H. Curtis, Federico J. A. Furch, Vyacheslav N. Shlyaptsev, Brad M. Luther, Dinesh Patel, Mario C. Marconi, Carmen S. Menoni, Colorado State Univ. (United States)

The generation of high average power beams of coherent soft x-ray radiation in a compact set up is of high interest for numerous applications. The average power of plasma-based soft x-ray lasers has been limited by the repetition rate of the solid state optical lasers that drive them, which typically comprise either flash-lamp-pumped neodymium-doped glass or titanium sapphire that are limited to about 10 Hz. To overcome this limitation we have developed a compact, directly diode-pumped CPA laser based on cryogenically-cooled Yb:YAG amplifiers that produces 1 Joule, 5 ps FWHM duration, λ=1.03 μm laser pulses at a record high repetition rate of 100 Hz. This laser was employed to drive a gain-saturated 18.9 nm soft x-ray laser in a nickel-like molybdenum plasma producing a record average power of ~0.15 mW [1]. Strong lasing at 13.9 nm was also achieved at 100 Hz repetition rate from a silver plasma. Optimized pump conditions for increased average power will be discussed. These results increase the repetition rate and average power of compact, sub-20 nm lasers by about an order of magnitude and are expected to extend the use of these lasers to new applications

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8849-10, Session 6

Performance of a beam-sharing monochromator at the Linac Coherent Light Source

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A diamond double crystal monochromator was recently commissioned at the Linac Coherent Light Source (LCLS). A 100 um thick strain-free single crystal diamond was used as the first crystal to split the beam: it reflects a narrow bandwidth and allows the remaining part of the incident spectrum to be delivered to downstream instruments. This would thus potentially allow simultaneous operation of several instruments at LCLS. We report here the initial characterizations of the monochromator performance including its bandwidth, throughput in both branches, and its impact on the wavefronts. Its implications on experimental operation and limitations are also discussed.

8849-23, Session 6

Status and achievements at FERMI@Elettra: the first double cascade seeded EUV-SXR FEL facility open to users *(Invited Paper)*

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FERMI@Elettra is the first VUV/soft X-ray FEL source based on the High-Gain Harmonic Generation (HGHG) configuration, in which an external UV laser is used to trigger the emission process. It is composed by two undulatory chains: the low energy branch (FEL1) covering the wavelength range from 20 nm up to 65 nm, and the the high energy branch (FEL2, employing a double stage cascade), covering the wavelength range from 4 nm up to 20 nm. At the end of 2012 FEL1 has been opened to external users while FEL2 has been turned on for the first time having demonstrated that a double cascade scheme is suitable for generating high intensity coherent FEL radiation. The Photon Analysis Delivery and Reduction System (PADReS) is used to provide information about the photon beam (intensity, spatial distribution and position, spectral content, transverse coherence,…) as well as for delivering and focusing the FEL radiation inside the experimental end-stations.

In our presentation we will share our experience and will show our most recent results for both FERMI FEL1 and FEL2 sources. We will also

present a brand new machine scheme that allows to perform two-colour pump and probe experiments as well as the first experimental results.

8849-24, Session 6

Single shot spectrum measurements of the fundamental, second, and third harmonic at a hard x-ray free electron laser

Matthieu Chollet, Henrik T. Lemke, Roberto Alonso-Mori, Marcin Sikorski, Yiping Feng, Aymeric Robert, Diling Zhu, SLAC National Accelerator Lab. (United States)

Most of the experiments performed to date at the Linac Coherent Light Source (LCLS) in the hard X-ray regime use the radiation from the fundamental wavelength. It was however shown that non-negligible levels of higher harmonics are also present [1] and can be used for experiments at higher photon energies beyond the reach of the fundamental wavelength. LCLS uses the principle of Self Amplified Spontaneous Emission (SASE), which introduces shot-to-shot fluctuations of many beam properties such as : pulse energy, pulse duration, spatial and temporal profile and spectral content. The understanding of how higher harmonics behave and correlate with the fundamental provides valuable information that can be used to improve data analysis, noise and background correction for LCLS operation.

We report here the measurement of both the fundamental and higher harmonic spectra of LCLS pulses using a single shot transmissive spectrometer for hard x-ray [2]. Two of those spectrometers based on bent thin Silicon crystals were used in this experiment. The first crystal dispersively diffracts the FEL spectrum at the fundamental wavelength, while higher harmonics are transmitted and diffract on a 2nd spectrometer ; thus enabling to record simultaneously both spectra from a single x-ray pulse.

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8849-25, Session 6

LCLS mirror switching of x-ray beam

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The number of proposals for LCLS science has rapidly increased as all six LCLS x-ray instruments have come online. Only about 25 % of LCLS proposals can be allocated beamtime. One way to increase access is to share the x-ray beam between the different instruments. The purpose of this study is to quickly switch the x-ray beam between the Materials under Extreme Conditions (MEC) Instrument and the Coherent X-ray Imaging (CXI) or X-ray Correlation Spectroscopy (XCS) Instruments, in order that two of the instruments can perform experiments simultaneously. In the most common operational mode, the MEC Instrument uses one x-ray pulse every 10 minutes, limited by the repetition rate of the high pulse energy nanosecond laser system. The MEC M3H mirror steers the x-ray beam to the MEC Instrument from the XCS or CXI Instruments. If the M3H mirror could switch the x-ray beam to MEC within a fraction of the 10 minute waiting time, multiplexing of the x-ray beam would be achieved. The M3H mirror system has two motion stages for translation and rotation. The long path, 230 m, from the mirror to MEC hutch makes the pointing resolution and stability requirements challenging. The mirror translation speed and pointing reproducibility have been investigated. This study has shown that mirror translation can multiplex the LCLS x-ray beam.

8849-26, Session 6

Scanning coherent x-ray microscopy as a tool for XFEL-nanobeam characterization

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The emergence of x-ray sources of the fourth generation, so called x-ray free-electron laser (XFELs), comes along with completely new research opportunities in various scientific fields [1, 2, 3, 4]. In some experiments, however, the XFEL-beam needs to be additionally focused in order to increase the fluence incident on a sample. The characterization of these nanofocused beams is often crucial for a quantitative analysis of experimental data. Nevertheless, since the peak intensity of these focused beams is well above the damage threshold of any material, the characterization of a nano-focused XFEL-beam is experimentally challenging and, to date, was pursued primarily by imprint techniques providing only postmortem information of the intensity distribution [5].

During the last years, scanning coherent x-ray microscopy, also called ptychography [6, 7, 8], has revolutionized nanobeam characterization at third generation x-ray sources. The method yields the complete information on the complex-valued, nanofocused wave field with high spatial resolution [9, 10]. In an experiment carried out at the Matter in Extreme Conditions (MEC) instrument at the Linac Coherent Light Source (LCLS) we successfully applied the method to an attenuated nanofocused XFEL-beam with a size of 125 nm (FWHM), which was created by a set of beryllium compound refractive lenses (Be-CRLs). The numerical analysis of the measured diffraction patterns gave access to the full caustic of the nanofocused beam. In a next step, the retrieved complex-valued wave field could be refined additionally for individual pulses.

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8849-28, Session 7

Development of x-ray sources using PW laser systems at APRI GIST *(Invited Paper)*

Hyung Taek Kim, I Jong Kim, Chul Min Kim, Ki Hong Pae, Jae Hee Sung, Seong Ku Lee, Tae Jun Yu, Tae Moon Jeong, Jongmin Lee, Chang Hee Nam, Gwangju Institute of Science and Technology (Korea, Republic of)

We present the status and the plans of developing x-ray sources using intense laser pulses at Advanced Photonics Research Institute (APRI), GIST. Up to date, we successfully demonstrated x-ray lasers and

relativistic high-order harmonics using 100-TW laser system. Recently, a PW laser system with 30-J energy and 30-fs pulse duration was developed at APRI and it has been applied to generate highly energetic charged particles. We are planning to generate high flux x-ray/gamma-ray sources using the PW laser system and high-energy particles.

8849-29, Session 7

Investigation of pathways to local thermodynamic equilibrium of autoionizing states driven by intense XFEL irradiation of solid matter

Frank B. Rosmej, Univ. Pierre et Marie Curie (France) and Ecole Polytechnique (France); Frederick Petitdemange, Univ. Pierre et Marie Curie (France)

High intensity XFEL interaction with matter creates exotic states of matter on fs-time scales with subsequent relaxation of the photoionized core hole states of almost every atom [1]. The non-equilibrium properties are therefore also linked to the autoionization processes. We show that the generally accepted pathway to local thermodynamic equilibrium in atomic level population physics where collisions need to be much more important than corresponding radiative decay rates is in general invalid for autoionizing states. The almost evident inclusion of the non-radiative decay (autoionizing rate Γ) on the same footing like radiative decay rates by simply requesting that collisional rates need to be much larger than the sum of autoionizing and radiative decay rates (neC>> A+Γ, ne is the electron density, C the collisional rate coefficient, A the spontaneous transition probability) may provide order of magnitude misleading critical densities above with LTE holds. By means of a detailed analysis of the population channels of autoionizing states that include excited state coupling effects, we have identified the condition neC>> A+Γ as a theoretical limiting case that is almost never achieved under real experimental conditions. Detailed calculations are carried out for Al for typical XFEL irradiation parameters to illuminate the correct pathway to LTE for autoionizing states.

[1] F.B. Rosmej: "Exotic states of high density matter driven by intense XUV/X-ray Free Electron Lasers", "Free Electron Laser", InTech 2012, editor S. Varró, p. 187 - 212, ISBN 978-953-51-0279-3.

8849-31, Session 7

Stimulated electronic x-ray Raman scattering with x-ray free-electron lasers *(Invited Paper)*

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X-ray free-electron lasers (XFELs) open the pathway to transfer non-linear spectroscopic techniques to the x-ray domain, to study the interplay of electronic and vibrational degrees of freedom by time-domain spectroscopy. A promising all x-ray pump probe technique is based on coherent electronic x-ray Raman scattering. The realization of these ideas is hampered by the extremely small inelastic scattering cross sections of x-rays with matter. A way to solve this problem is to stimulate the scattering process.

We present results on the first experimental demonstration of nearly saturated stimulated electronic x-ray Raman scattering using the LCLS XFEL. By tuning the relatively broad XFEL pulses to the core-excited Rydberg resonances in the pre K-edge region of neon, resonance scattered photons drive an avalanche of resonant inelastic x-ray scattering events. The scattering process is seeded by the spectral tail of the XFEL pulse, resulting in exponential amplification of the scattering signal with an enhancement of 6-7 orders of magnitude compared to the number of seed photons. By analyzing the line profile of the emitted radiation, the cross over from amplified fluorescence to a coherent resonance scattering was demonstrated. In case of coherent scattering, the scattered x-ray radiation shows a pulse-to-pulse fluctuation of the line shape and the spectral peak position, resulting from a stochastic detuning of individual spectral spikes of the XFEL from resonance. In combination with statistical covariance mapping, a high-resolution spectrum of the resonant inelastic x-ray scattering process can be obtained, opening the path to coherent stimulated x-ray Raman spectroscopy.

8849-32, Session 8

Coherent nanopatterning with table-top soft x-ray lasers *(Invited Paper)*

Mario C. Marconi, Lukasz Urbanski, Wei Li, Colorado State Univ. (United States); Aaron G. Stein, Brookhaven National Lab. (United States); Carmen S. Menoni, Jorge J. Rocca, Colorado State Univ. (United States)

We describe the last achievements in coherent lithography utilizing table top soft X ray lasers. This lithographic approach represents an interesting alternative for small scale nanofabrication of periodic structures. A periodic object composed of a two dimensional array of tiles forms highly accurate real images of itself by the classic Talbot self imaging effect. The Talbot images are used to print a photoresist deposited on a sample located in the Talbot plane where the self-image is produced. The print in is used to further process the sample and define periodic metallic nanostructures.

The diffractive mask was fabricated on a 25 nm thick membrane of Si3N4 using standard electron-beam lithography. The pattern was directly created in a 65 nm thick hydrogen silsesquioxane (HSQ) photoresist layer, or alternatively was etched through to create a self-standing diffractive mask. A soft X-ray =46.9 nm capillary discharge laser was used to replicate the Talbot mask.

We will present experimental results showing that the Talbot lithography method is scalable in size changing the convergence of the illumination beam, achieving de-maginification factors in the print of about 20%. Also this lithographic technique is capable to produce defect-free prints. Different examples of periodic structures fabricated in Au and Ag will also be presented.

8849-33, Session 8

Two-zone-plate interferometer for EUV image-plane holographic microscopy

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We present a new interferometric technique employing coherent radiation from a table-top capillary discharge Ar laser operating at 47nm. Using zero and first diffraction orders of successively placed binary Fresnel zone plates that act like both focusing elements and beam-splitters we can acquire an image-plane hologram of the sample evaluating quantitatively both the phase and amplitude effects of the sample. Besides the theoretical estimation of the performance of the technique we report a test experiment with nanostructured Si sample. The estimated spatial resolution of our setup reached 100nm due to high numerical aperture of the objective zone plate and short wavelength of the radiation. Although, the pulse duration of the Ne-like Ar laser was 1.5ns setting the limit of temporal resolution of our setup when operated in single-shot regime, the demands on longitudinal coherence of the interferometer are due to its in-line configuration rather low enabling to reach 100fs temporal resolution, if appropriate source of radiation was used.

8849-34, Session 8

Tabletop coherent diffraction imaging with a discharge plasma EUV source

Larissa Juschkin, Lars Loetgering, RWTH Aachen (Germany); Jianwei Miao, Univ. of California, Los Angeles (United States)

We present results of lensless imaging experiments using a high-frequency tabletop discharge plasma based partially coherent extreme ultraviolet (EUV) source. Influence of spatial and temporal coherence is investigated experimentally and compared with theoretical predictions for two emission spectra of different bandwidth at 11 nm and 17.3 nm. By using different illumination pinhole geometries, beams of varying degree of spatial coherence are generated and utilized to obtain far field diffraction patterns for iterative reconstruction of the complex transmission function of a test object. The presented experiments explore the feasibility of coherent diffraction imaging (CDI) with high brightness sources emerged from the technology development of EUV lithography, paving the way for laboratory-scale CDI applications in nanoscience and metrology.

8849-35, Session 8

Recent developments in the theory of coherent x-ray imaging

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Coherent imaging is a well developed technology both in the visible and X-ray ranges. It can be applied if coherent sources such as lasers, harmonic generators or 3rd and 4th generation light sources are used for object illumination. Coherent imaging provides a combination of useful modalities: phase retrieval, lensless imaging, wavelength resolution and also reduces the radiation loading on the object and environment. Traditionally coherent imaging was used mainly for investigation of transparent objects. Our approach based on the parabolic wave equation allows extending the method to imaging in the reflection mode including the objects illuminated at grazing angles of incidence. The earlier suggested “transparent” boundary conditions we widely use for analysis and computing of object to detector wave field propagation. If the object is tilted in respect to the beam k-vector the wave field is found in the form generalizing the Fresnel integral widely used in the theory of transmission mode coherent imaging. The inversion of this new expression for the wave field is a basis for solution of the phase retrieval problem in the case of obliquely illuminated objects. The optical schemes for coherent reflection imaging are presented and relations between coherent and geometrical optics images are found. The results are illustrated with the help of computer codes developed for evaluation of spatial resolution and field of view.

8849-42, Session PWed

Diamond crystals and a novel strain-free crystal mount for beam sharing double-crystal monochromator at LCLS

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A double-crystal diamond monochromator recently implemented at the LCLS enables splitting of the XFEL beam for simultaneous operation of two beamlines. The first crystal of the monochromator is a high quality type IIa diamond crystal plate with (111) surface orientation and of ~ 100 um thickness (to reduce absorbtion in the transmitted beam). We present details on the crystal fabrication, a novel method for strain-free crystal mount and results of x-ray characterization.

In particular, type IIa diamond crystal plates were cut by a laser into ~150 um thickness with small angular offset from (111) surface orientation (to enable polishing down to ~10 nm rms surface roughness.

The crystals were characterized by Lang x-ray topography and white-beam synchrotron topography. Plates with nearly perfect, defect-free regions of 2x5 mm2 were selected. These crystal plates were mounted on CVD diamond substrates and held gently by clams made out of diamond. The stiffness of the clamps was refined until strain-free rocking curve images (evaluated by doube-crystal x-ray topography) were obtained.

One of these assebmblies was installed in a vaccum tank of a large offset monochromator at the LCLS to enable beam sharing. Preliminary results indicate no substantial temperature gradients in the diamond-on-diamond assembly, absence of radiation damage and stable performance of the monochromator.

8849-43, Session PWed

Beam characteristics of CAPEX XUV argon laser

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The soft X-ray and extreme ultraviolet (XUV) lasers are sources, the applicability of which to technological and scientific research appeared just only about twenty years ago. These lasers were used for e.g. high-resolution microscopy, nanolithography, micro holography, and at very high plasma density measurements. The main advantages of these lasers are their availability, cost-effectiveness, and compactness. Such soft X-ray/XUV lasers have come in use in scientific and industrial laboratories for various applications.

Our department has been studying high-current capillary discharge as a XUV laser source over past 15 years. We are successfully operating two experimental devices CAPEX and CAPEX-U and we have observed a very strong amplification of Ne-like argon line at 46.9 nm on both these devices. While the experimental apparatus CAPEX-U has laser-triggered spark gap, which enables exact synchronization with diagnostics or other attached experiments, the apparatus CAPEX is capable to run at a higher repetition rate (~ 1 Hz).

This paper will report on the experimental results of CAPEX apparatus (repetitive lasing), mainly on its beam characteristics (e.g. laser beam profile, and laser pulse energy).

8849-44, Session PWed

Molecular dynamics simulation of cluster formation in femtosecond laser ablation

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Laser ablation using an ultrashort pulse is expected to be applied in a wide range of areas and has been intensively investigated by a lot of experiments so far.

However, ablation processes by laser irradiation is complicated; therefore, a detailed analysis needs theoretical approaches especially for nonequilibrium and noncontinuum regime that appears in a picosecond-order dynamics.

In this paper, we present the ablation processes of platinum caused by a femtosecond laser pulse using a three-dimensional molecular dynamics model combined with the two-temperature model.

We can classify the ablation dynamics into three categories by clustering features which depends on a laser fluence above the ablation threshold.

With low laser fluence, spallation is found since the surface layer of the solid target breaks away due to a tensile pressure wave.

Homogeneous nucleation of nano-size clusters takes place with middle fluence in the liquid layer after the target surface layer is superheated and melts, although the surface layer fragments and vaporizes with higher fluence, which results in the gasification of the target.

We have examined the cluster formation of the ablated platinum above the ablation threshold by varying laser fluence and characterized these categories in terms of size distribution of the emitted cluster.

The size distribution obeys a power-law for the high laser fluence, while plateau region is found for the middle fluence.

Furthermore, the mechanism of the difference among three formation types may be explained -balance between the laser-induced pressure and binding energy of the atoms.

8849-36, Session 9

Multiple pulses pumping for application-oriented soft x-ray laser sources *(Invited Paper)*

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Low energy laser pulses, prior to the main high intensity pulse, are playing a crucial role in laser plasma interaction, as they can induce substantial modification of the target. Usually seen as detrimental, they are playing a dramatic and helpful role in soft x-ray laser generation both in QSS [1-2] and TCE [3-5] regimes. Implementing a train of prepulses in a controlled way, keeping the setup easy to use and stable is of great importance for a facility providing XUV beams for applications.

After a general overview of the technical solutions developed on the Laserix facility, we will illustrate how to choose one particular technique to match experimental requirements. Three examples will be highlighted. We will first present studies on a multiple pulse, single beam scheme and show how this configuration is helpful for reaching high stability and long operation cycle (at 10Hz) with a short preparation time. This kind of method has been successfully tested during experiments requiring an accumulation of a large number of shots (DNA sample irradiation, measurement of the reflectivity of a magnetic sample…)[6].

Pump-probe experiments are usually requesting auxiliary beams with a high contrast, which is in contradiction with most of the previously described methods. A very simple and efficient alternative has been demonstrated to overcome this problem. An auxiliary, low cost, Q-switch Nd:Yag laser, electronically synchronized with the IR laser, can play the role of a train of prepulses and can reach up to one third of the required ionisation level of Ni-like silver. In many ways this device is close to the one presented in [3] but the high contrast infrared pulse is preserved. Some variations of this technique will be detailed including the implementation of a short ionising pulse as proposed in reference [7]. The practice of this scheme will be illustrated by a pump-probe experiment dedicated to warm dense target XUV opacity probing [8].

Finally, soft x-ray laser seeding with high order harmonics could benefit from these methods. Effect on plasma uniformity, on gain linewidth, and on real seeding operations will be discussed.

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8849-37, Session 9

Probing of laser-irradiated solid targets using coherent extreme ultraviolet radiation

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It is planned that x-ray free-electron lasers (XFELs) will have large synchronised lasers, so laser-plasma probing studies using XFELs will be possible. Due to these future possibilities with XFELs and the possibility of undertaking such measurements with coherent harmonic radiation at existing facilities, the potential for coherent extreme ultra-violet (EUV) light in probing laser-produced plasmas is investigated in this work. A fluid code is used to model the interaction of a 35 fs, 2x1014 Wcm-2 800 nm laser pulse on an 800 nm thick aluminium target with a post processor used to calculate the refractive index and transmission of 45eV radiation through the target. The effects of EUV radial phase variations at the rear of the target on the intensity distribution at a detector 1.5m from the target are studied. The irradiated aluminium target is found to have little effect on the transmission of the 45eV radiation, but there are significant phase retardation effects on the probing beam. These phase variations change the subsequent propagation of the radiation, suggesting a simple diagnostic measuring the far-field footprint of coherent EUV radiation passing through an irradiated target is sensitive to radial variations of the target heating. More general issues involved in the use of EUV light in probing plasmas of relevance to inertial fusion will also be discussed.

8849-38, Session 9

High energy density plasmas produced by x-ray and extreme ultraviolet lasers

Andrew K. Rossall, Valentin Aslanyan, Gregory J. Tallents, The Univ. of York (United Kingdom)

The work presented here examines the EUV/x-ray interaction within solid material, incorporating a detailed photoionization model into a pre-existing 2D Eulerian fluid code POLLUX. This code is used to investigate the ablation and expansion of the target material under intense EUV irradiation in order to investigate; the high aspect ratio, hole-drilling capabilities of an EUV/x-ray laser; the properties of the produced ‘bleaching wave’; the significant increase in ejected mass; and to simulate and interpret results from mass spectrometry measurements of solid density and expanding plume plasmas.

High energy density plasmas can be produced in both non-equilibrium

and equilibrium states through the interaction of x-ray and EUV laser sources with solid targets. EUV and x-ray lasers with wavelengths less than around 50nm can propagate through plasma at solid material density, as even with high levels of ionisation, the free electron density is sub-critical. Direct heating of solid density material arising from inverse bremsstrahlung, photoionization and autoionization can occur producing a rapid drop in opacity or a 'bleaching' of the target.

This work has significant impact potential in the areas of; the production of warm dense matter relevant to ICF; in high aspect ratio laser cutting, relevant to microelectromechanical systems; and use in plasma coating techniques.

8849-39, Session 9

Efficiently excited ultra-hot capillary discharge plasmas

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The scaling of discharge plasma parameters represents a difficult task. As compared with laser-created plasmas, discharges impose more constrains. Aside from disruptive magnetic instabilities, which capillary plasmas can nearly miraculously overcome, in pinch discharges the two key mechanisms of energy deposition, magnetic pressure and Joule heating, are inter-dependent and both contribute to define energy distribution, plasma lifetime and other plasma parameters.

Motivated by the possibility of advancing x-ray lasers utilizing electrical discharges we are investigating a novel capillary discharge approach that promises to yield simultaneously high temperatures, high densities and high degree of ionization with high efficiency. To achieve this we are investigating a somewhat anti-intuitive approach, opposite to that of simply rising the peak current and following the route of large facilities with MA currents. Instead we are using ultrafast current pulses of modest amplitude and optimize the heating parameters to obtain increased efficiency of energy deposition into the plasma.

We developed an ultrafast electrical current pulser for driving into narrow bore channels discharges with an order of magnitude faster risetime than used in our previous Ne-like argon x-ray laser research. We are conducting experiments with currents of ~30-40 kA amplitude with the aim of demonstrating uniquely high plasma parameters, defined by electron temperatures and degree of ionization only comparable to those we have obtained using 200 kA current pulses. The results of detailed simulations will be compared to experiments, and applications to soft x-ray laser development will be discussed.

8849-40, Session 10

Development of coherent EUV scatterometry microscope with high-order harmonics for EUV mask inspection *(Invited Paper)*

Yutaka Nagata, RIKEN (Japan) and Univ. of Hyogo (Japan) and JST CREST (Japan); Tetsuo Harada, Masato Nakasuji, Hiroo Kinoshita, Univ. of Hyogo (Japan) and JST CREST (Japan); Katsumi Midorikawa, RIKEN (Japan)

Extreme ultraviolet (EUV) is the most promising technology for high volume manufacturing of next generation semiconductor. There is urgent need for stand-alone inspection tool for EUV mask. At wavelength inspection will be required for precision detection and evaluation of defects in EUV mask. A EUV mask consists of a patterned absorber on top of a reflective Mo/Si multilayer deposited on glass substrate. In the preliminary research, we have developed a coherent EUV scatterometry microscope (CSM) based on coherent diffraction imaging method using synchrotron radiation. Aerial images were reconstructed from diffraction images using phase retrieval algorithm. The CSM required spatially and temporally coherent EUV light to achieve a high spatial resolution. Since the synchrotron radiation was partially coherent, EUV power on the mask was reduced to about 1 pW as a result of improvement of the coherence. But coherence of the EUV source was still not sufficient for the detection of small defects. We have developed a coherent high-order harmonics generation system as a practical coherent EUV light source for the CSM. Low divergence, spatially coherent, high-order harmonics (HHs) have been generated using commercial sub-TW laser system. The CSM equipped with 13.5 nm HHs dramatically improved the contrast ratio of diffraction images. Defect signals were observed from the 2-nm width line-defect in the 88-nm line-and-space (L/S) pattern. The diffractive light patterns caused by hole defects were distinguished with intense interference patterns caused by two-dimensional periodic hole-patterns. We also observed bridge defects in the 88-nm L/S pattern.

8849-41, Session 10

X-ray Thomson scattering for partially ionized plasmas including the effect of bound levels

Joseph Nilsen, Lawrence Livermore National Lab. (United States); Walter R. Johnson, Univ. of Notre Dame (United States); K. T. Cheng, Lawrence Livermore National Lab. (United States)

X-ray Thomson scattering is being developed as a method to measure the temperature, electron density, and ionization state of high energy density plasmas such as those used in inertial confinement fusion. Most experiments are currently done at large laser facilities that can create bright X-ray sources, however the advent of the X-ray free electron laser (X-FEL) provides a new bright source to use in these experiments.

One challenge with X-ray Thomson scattering experiments is understanding how to model the scattering for partially ionized plasmas in order to include the contributions of the bound electrons in the scattered intensity. In this work we take the existing models of Thomson scattering that include elastic ion-ion scattering and the electron-electron plasmon scattering and add the contribution of the bound electrons in the partially ionized plasmas. We will first look at the bound electron contributions to beryllium by analyzing existing experimental data. We then consider several higher Z materials such as Cr and predict the existence of additional peaks in the scattering spectrum that requires new computational tools to understand. We will also show examples of experiments in C and Al that have bound contributions that change the shape of the plasmon peaks in a way that would change the plasma temperature and density inferred by the experiment.

8850-1, Session 1

Target alignment and positioning on the Astra-Gemini facility

Nicola Booth, Daniel Symes, David Neely, Oliver Ettlinger, Andrew Sellers, Central Laser Facility (United Kingdom)

The drive to higher intensities and the move to shorter focal length reflective optics for focussing in solid target interactions are increasingly important for studies into high intensity secondary source generation, QED studies and the push for inertial confinement fusion. This then presents a significant problem for accurate target positioning. Commercial imaging systems exist to aid the imaging and positioning of targets, however these are expensive and difficult to position areas of limited space.

At the Astra-Gemini system of the Central Laser Facility, the push for intensities above I = 10^21 Wcm^-2 with f/2 and f/1 optics means positioning targets within the Rayleigh range of < few microns. Here we present details of 2 systems implemented on the Astra-Gemini system to cheaply and accurately position targets with ≈ micron accuracy. These involve a cheap multi-achromat lens system with illumination at 800nm (the same as the Gemini IR beam) for imaging the rear of the target with high resolution and a multi-wavelength interferometer to enable sub-micron accuracy in the positioning of the front surface at the interaction point within the Rayleigh range. The combination of these two systems has significantly improved our accuracy in target positioning and has also resulted in a decrease in the time required to align targets between shots.

8850-2, Session 1

Evaluating radiation induced noise effects on pixelated sensors for the National Ignition Facility

Philip S. Datte, Anastacia M. Manuel, Mark J. Eckart, Mark C. Jackson, Hesham Y. Khater, Mark A. Newton, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) utilizes several different pixelated sensor technologies for various functional measurement systems that include alignment cameras, laser energy sensors, and high-speed framing cameras. These systems remain in the facility where they are exposed to neutron radiation during a NIF shot. The image quality of the sensor degrades as a function of radiation induced damage. When a neutron strikes an individual pixel, it increases the noise by increasing its dark current response. This article reports on a figure-of-merit technique that aids in the tracking of the performance of pixelated sensors when exposed to neutron radiation from NIF. The technique displays the sensor dark current response normalized to the well depth versus the normalized number of pixels that have that response or better (lower noise). In essence, this is the cumulative sum for the probability distribution of pixels for dark current response. The sensor dark current growth can be displayed over time in a 2D visual representation for tracking radiation induced damage. Predictions to the increased noise as a function of neutron fluence for future NIF shots allow systems to simulate reduced performance for each of the individual camera applications. This predicted longevity allows for proper management of the camera systems.

8850-3, Session 1

Nuclear background effects on plasma diagnostics for megajoule class laser facility

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Estimating the vulnerability is a key challenge for plasma diagnostics designed to operate in radiative background associated with megajoule class laser facility. Since DT shots at OMEGA laser facility reproduces the perturbing source expected in the first 100 nanoseconds of a typical DT shot on National Ignition Facility and Laser MegaJoule, vulnerability of diagnostic elements such as optical relays or optical analyzers are experimentally studied and if necessary hardening approaches initiated to ensure their survivability at higher constraints.

A set of three different optical relays associated with optical analyzer have be exposed to 5.10^13 neutrons yield at 5 m from the OMEGA target chamber center. Degradations are observed, especially for the recording device (CCD) for which dynamic range appears proportional to the neutron fluence. An optical architecture is then extremely sensitive to the radiative environment and in standard configuration will lead to complete failure of diagnostic when extrapolating to NIF or LMJ fluence.

A new mitigation technique improving radiation tolerance of diagnostics based on CMOS image sensor has been tested at OMEGA facility to overcome this vulnerability problem. Charges generated by particles impinging the sensor are removed thanks to a custom global reset functionality. The image, free of transient degradation, is recorded only when the radiation constraints have faded away with a long persistence scintillator. In complement, simulations are led to predict the remaining transient and permanent degradation of image sensors in complex radiative background.

8850-4, Session 1

Diagnostic Instrument Manipulator (DIM) upgrades for reliability and operational efficiency in a radiological contamination environment at the National Ignition Facility

Robert E. Plummer, Lawrence Livermore National Lab. (United States)

The Diagnostic Instrument Manipulators (DIMs) are two-staged, telescoping systems that allow the precise alignment and positioning of various x-ray, optical, nuclear, and other diagnostics in the National Ignition Facility (NIF) Target Chamber. Designed to be reconfigurable and exchangeable between NIF experiments, the second stage of the DIM is referred to as the Diagnostic Load Package (DLP), which is most often comprised of a cart, diagnostic, and detachable snout. As experiments continue to increase radiation levels, various upgrades have been made to the DIMs to improve reliability and operational efficiency. These upgrades reduce worker exposure and increase experimental shot rates. Specific to this paper, the design and operation of dedicated DLP handling and storage units (DHUs and DSUs) are discussed in addition to their transport equipment. Hardware and process improvements for reduced worker exposure during general DIM access are also featured. Finally, the DLP limit switches have been upgraded to magnetically-

actuated proximity sensors for reliability, improved shot rate, and increased user flexibility.

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8850-5, Session 2

Calibration and modeling of x-ray and neutron sensitivity of imaging plates

Nobuhiko Izumi, Gary F. Stone, Brian R. Maddox, David K. Bradley, Perry M. Bell, Lawrence Livermore National Lab. (United States); Joshua J. Lee, Edward Don M. Lomano, National Security Technologies, LLC (United States)

An imaging plate (IP) is a phosphor with signal storage capability. Due to their immunity to electric-magnetic-interference, IPs have been used in various laser-plasma experiments as a time integrating detector for x-ray imaging and electron spectroscopy.

In a sensitive region of an IP, electrons produced by ionizing radiation are trapped by color centers (vacancies of F,Br, or I). When the plate is scanned with a laser beam (650nm), those trapped electrons are re-excited and cause photo stimulated luminescence (~390 nm) by recombination. Each type of IP has different composition and physical thickness. The readout efficiency of the stored signal also depends on laser power, spot size, and scanning speed of the scanner. A signal fading due to thermal excitation of trapped carrier also affects the sensitivity of IP's. In order to extract quantitative information from IP data, it is crucial to calibrate the sensitivity of the plate together with the scanner. We present an easy to use IP calibration station based on radioactive isotopes (55Fe, 109Cd, and 241Am). This apparatus provides a convenient setup for measuring absolute sensitivity of the IP and the associated scanner. Comparison of experimental results and Monte Carlo simulations will be reported. An absolute sensitivity measurement of IPs for fast neutrons will also be reported. Prepared by LLNL under Contract DE-AC52-07NA27344.

8850-6, Session 2

Calibrating image plate sensitivity in the 700 to 5000 eV spectral energy range

Michael J. Haugh, Joshua J. Lee, Edward D. Romano, National Security Technologies, LLC (United States); Marilyn B. Schneider, Lawrence Livermore National Lab. (United States)

This paper describes a method to calibrate image plate sensitivity for use in the low energy spectral range. Image plates can be a valuable tool as a detector for plasma physics studies. Their advantages of large dynamic range, high stopping power, and resistance to neutron damage sometimes outweigh the problems of limited resolution and the remote processing required. The neutron damage resistance is required when using the Static X-ray Imager on the National Ignition Facility (NIF) target chamber at LLNL on high yield shots.

Type MS and SR image plates were calibrated and published for spectral sensitivity from 8 to 80 keV using the NSTec High Energy X-ray (HEX) source1, a fluorescer type X-ray source. Models MS and SR have a plastic coating, model TR has no coating. The models SR and TR were calibrated at the low energy range using a diode source and a band pass filter. The X-ray flux is measured using a photodiode that is traceable to NIST. The spectrum for each X-ray band is measured using a silicon drifted detector. The image plate metastable states are converted to digital images using a standard reader. The results of these measurements will be presented and the uncertainties in the measurement will be discussed. The results will be compared to other measurements and estimation methods.

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8850-7, Session 2

Development of CCD cameras for soft X-ray imaging at the National Ignition Facility

Alan T. Teruya, Nathan E. Palmer, Marilyn B. Schneider, Lawrence Livermore National Lab. (United States); Gary R. Sims, Spectral Instruments, Inc. (United States); Michael J. Haugh, Edward D. Romano, Dennis T. Palmer, National Security Technologies, LLC (United States)

The Static X-Ray Imager (SXI) is a National Ignition Facility (NIF) diagnostic that uses a CCD camera to record time-integrated X-ray images of target features such as the laser entrance hole of hohlraums. SXI has two dedicated positioners on the NIF target chamber for viewing the target from above and below, and the X-ray energies of interest are 870 eV for the "soft" channel and 3 – 5 keV for the "hard" channels. The original cameras utilize a large format back-illuminated 2048 x 2048 CCD sensor with 24 micron pixels. Since the original sensor is no longer available, an effort was recently undertaken to build replacement cameras with suitable new sensors. Three of the new cameras use a commercially available front-illuminated CCD of similar size to the original, which has adequate sensitivity for the hard X-ray channels but not for the soft. For sensitivity below 1 keV, LLNL had additional CCDs back-thinned and converted to back-illumination for use in the other two new cameras. In this paper we describe the characteristics of the new cameras and present performance data (noise, dynamic range, and energy sensitivity) for the front- and back-illuminated cameras, with comparisons to the original cameras. Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

8850-8, Session 2

Performance of CID camera X-ray imagers at NIF in a harsh neutron environment

Nathan E. Palmer, Marilyn B. Schneider, Kenneth W. Piston, James D. Moody, Lawrence Livermore National Lab. (United States); Michael J. Haugh, Joshua J. Lee, National Security Technologies, LLC (United States)

Charge-injection devices (CIDs) are 2D imaging sensors similar to CCDs, but their distinct architecture makes CIDs more resistant to ionizing radiation. CID cameras have been used extensively at the OMEGA Laser Facility for X-ray imaging with neutron fluences at the sensor approaching 10^9 neutrons/cm2 (DT, 14.1 MeV). A CID Camera X-ray Imager (CCXI) system has been designed and implemented at NIF that can be used as a rad-hard electronic-readout alternative for time-integrated X-ray imaging. This paper describes the design and implementation of the system, sensitivity of the sensor for X-rays in the range of 2 – 15 keV, and data acquired on NIF shots over a range of neutron yields. The upper limit of neutron fluence at which CCXI has acquired useful data is somewhat lower than the expected 109 neutrons/cm2 and there are noise problems that require further work, but the sensor has proven to be very robust in surviving high yield shots with minimal damage. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

8850-9, Session 2

Characterization of a megapixel CMOS charge dump and read camera

Joseph R. Kimbrough, Perry M. Bell, James D. Moody, Mai Thao, Lawrence Livermore National Lab. (United States)

The National Ignition Facility is developing a radiation-hardened megapixel CMOS imaging camera to replace CCD cameras currently

used in x-ray streak cameras and gated imaging detectors. A prototype radiation tolerant camera based on a 2k by 2k CMV4000 sensor from CMOSIS Inc. has been built. Camera electronic parts were selected to operate up to 10 krad(Si). The sensor and camera incorporate a fast charge and dump of the sensor pixels, followed by image readout. This allows the dumping of charge due to the prompt radiation noise and then readout of the longer persistence phosphor signal from the x-ray diagnostics. Characterization of the sensor and gated performance were completed. This will be followed with characterization of radiation effects on the sensor and camera.

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8850-10, Session 3

M-ARIANE: an x-ray imaging system for implosion experiments on National Ignition Facility at ignition neutron yields

Vladimir Smalyuk, Lawrence Livermore National Lab. (United States)

X-ray imaging diagnostics instruments will operate in a harsh ionizing radiation background environment during ignition experiments at the National Ignition Facility (NIF). These backgrounds consist of mostly neutrons and gamma rays produced by inelastic scattering of neutrons. An imaging system M-ARIANE, based on x-ray framing camera with film, has been designed to operate in such harsh neutron-induced background environments. Multilayer x-ray mirror and a shielding enclosure are the key components of this imaging system, designed to operate at neutron yields of ~1e18 on NIF. Modeling of the signal and noise of the x-ray imaging system will be presented.

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8850-11, Session 3

Design and implementation of Dilation X-ray Imager for NIF "DIXI"

Marion J. Ayers, Sabrina R. Nagel, Perry M. Bell, Brian Felker, David K. Bradley, Kenneth W. Piston, Jake M. Parker, Lawrence Livermore National Lab. (United States)

Gated X-Ray imagers have been used on many ICF experiments around the world for time resolved images of the target implosions. DIXI (Dilation X-ray Imager) is a fixed base diagnostic that has been developed for use in the National Ignition Facility. The DIXI diagnostic is comprised of the following subsystems, pinhole imaging, filtering cassette, EMI shielding, pulsed dilation technology [1], detector head, detector head electronics, control electronics, CCD, film recording and nearly 1 ton of neutron shielding. Here we discuss the initial design, improvements implemented from rigorous testing, infrastructure and commissioning of DIXI on NIF.

8850-12, Session 3

X-ray yield measurements >6keV using a hardened streak camera at the National Ignition Facility

Shahab F. Khan, Andrew G. MacPhee, Kathy P. Opachich, Joseph R. Kimbrough, Joe P. Holder, Nobuhiko Izumi, Perry M. Bell, David K. Bradley, Lawrence Livermore National Lab. (United States); Joshua J. Lee, Michael J. Haugh, National Security Technologies, LLC (United States)

A neutron hardened x-ray streak camera has been used to report x-ray burn duration and time of peak emission from imploding ICF capsules at The National Ignition Facility with ? <30 ps. Recent calibration of the instrument using a NIST traceable High Energy X-ray reference source (HEX, National Security Technologies) has enabled absolute capsule self-emission x-ray yield measurements (J/sr/keV). In this (talk/poster) we describe the calibration procedure used and present preliminary x-ray yield measurements from recent ICF implosions and compare results with time integrated yield data.

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8850-13, Session 3

A Kirkpatrick-Baez optic for x-ray diagnostic at NIF

Tommaso Pardini, Lawrence Livermore National Lab. (United States)

At the Lawrence Livermore National Laboratory (LLNL) we are developing a Kirkpatrick-Baez (KB) optic to be added to the suite of x-ray diagnostic instruments for the National Ignition Facility (NIF). The optic consists of 4 KB pairs made of spherically polished x-ray substrates. These substrates are multilayer-coated to allow steeper grazing angle geometries, and wavelength filtering. With this optic we aim at providing NIF with an alternative x-ray imaging technique to pinholes, improving both resolution and photon throughput. Extensive analysis has been conducted to define optic parameters compatible with the requirements of typical NIF experiments, such as core implosion and backlighter experiments. Here we intend to give an overview of the current design for the optic, and show simulation results of optic performance. Simulations have been obtained via ray tracing and wavefront propagation code.

8850-14, Session 4

Measuring the hot-electron population using time-resolved hard x-ray detectors on the NIF

Matthias Hohenberger, Univ. of Rochester (United States); Nathan E. Palmer, Gregory A. LaCaille, Eduard L. Dewald, L. Divol, Essex J. Bond, Tilo Doeppner, Lawrence Livermore National Lab. (United States); Joshua J. Lee, National Security Technologies, LLC (United States); C. A. Thomas, David K. Bradley, B. Kauffman, Lawrence Livermore National Lab. (United States); Christian Stoeckl, T. Craig Sangster, Univ. of Rochester (United States)

In laser-driven inertial confinement fusion, hot electrons can preheat the fuel and prevent compression of the capsule to ignition conditions. Measuring the hot-electron population in these high-intensity laser-driven experiments is key to understanding the laser–plasma interaction and the resulting target evolution. This can be inferred from the Bremsstrahlung generated by the interaction of the hot electrons with the target. At the National Ignition Facility (NIF), the filter-fluorescer x-ray diagnostic (FFLEX), a multichannel, hard x-ray spectrometer operating in the range of 20 to 500 keV, has recently been upgraded to fully time-resolved measurements of the Bremsstrahlung spectrum. We present characterization data for the upgraded setup, as well as recent results from ignition-scale experiments.

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8850-15, Session 4

Operational experience with optical streak cameras at the National Ignition Facility

Philip S. Datte, Peter M. Celliers, Daniel H. Kalantar, John D. Moody, Jarom Nelson, Randy T. Shelton, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) utilizes several optical streak camera systems that collect data from (350nm to 1053nm) band during a full system laser shot. The camera systems are configured to collect single or multiple intensity profile signals, spectrally resolved data, spatially resolved interferometry data, and spatially resolved intensity data. The output data format represents the temporal resolution of the recorded event as a two dimensional image. For all these configurations, the time record ranges from 3ns to 100 ns. The precision of the recorded data requires several calibration techniques that provide an overall 2D space-time warp correction that is applied to the raw streak data. The article shall review the typical applications of the optical streak cameras on NIF, the performance of the calibration applied to shot data while in operation and the overall performance and reliability of the camera systems over the several years of operation.

8850-16, Session 4

Mach-Zehnder modulator performance on the NIF south pole bang time diagnostic

Bart Beeman, Andrew G. MacPhee, Joseph R. Kimbrough, Robert Chow, Essex J. Bond, Lawrence Livermore National Lab. (United States); K. Miller, National Security Technologies, LLC (United States); William R. Donaldson, Univ. of Rochester (United States)

We present performance data for Mach-Zehnder optical modulators fielded on the National Ignition Facility as a potential signal path upgrade for the South Pole Bang Time diagnostic. A single channel demonstration system has been deployed utilizing two modulators operating 90deg out of phase with each other extending the system dynamic range and improving signal to noise capabilities. X-ray target emission signals are split and fed into two recording systems; a reference CRT based oscilloscope and the dual Mach-Zehnder system. Results of bang-time determination from these two recording systems are compared and presented.

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8850-17, Session 5

2D magnetic field warp reversal in images taken with DIXI (dilation x-ray imager)

Sabrina R. Nagel, Perry M. Bell, David K. Bradley, Marion J. Ayers, Brian Felker, Kenneth W. Piston, Gilbert W. Collins, Lawrence Livermore National Lab. (United States); Terance J. Hilsabeck, Joseph D. Kilkenny, Tae Chung, B. Sammuli, General Atomics (United States); Jonathan D. Hares, A. K. Dymoke-Bradshaw, Kentech Instruments Ltd. (United Kingdom)

DIXI utilizes pulse-dilation technology [1] to achieve x-ray imaging with temporal gate times below 10 ps [2]. The longitudinal magnetic field used to guide the electrons during the dilation process results in a warped image, similar to an optical distortion from a lens. Since the front end, where x-rays are converted into electrons, at the beginning of the magnetic field determines the temporal resolution these distortions influence the temporal width of the images at the back end. Here we discuss the measurements and methods used to reverse the magnetic warp effect in the images gathered. The x-ray measurements were conducted using the COMET laser facility at the Lawrence Livermore National Laboratory.

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LLNL-ABS- 618072

8850-18, Session 5

Investigation and suppression of artifacts in x-ray framing cameras due to advance radiation incident on microchannel plates

Laura Robin Benedetti, Charlie S. Anderson, Perry M. Bell, David K. Bradley, Charles G. Brown Jr., Steven M. Glenn, Joe P. Holder, Joseph R. Kimbrough, Michael P. Perkins, Robert B. Petre, Kenneth W. Piston, Natalia Simanovskaia, Lawrence Livermore National Lab. (United States)

We present evidence of an artifact in gated x-ray framing cameras that can severely impact image quality. This artifact typically presents as a high-intensity background over a narrow central portion of each microstrip of the framing camera and is correlated with experiments that produce a high flux of x-rays during the time before the framing camera is triggered.

Dedicated experiments using a short-pulse UV laser confirm that these artifacts can be most effectively produced by light that arrives ~1ns in advance of the voltage pulse that triggers the camera. This is consistent with these artifacts being the result of electrons produced uniformly at the MCP by early incident light and then focused by the EM fields of the camera.

We also describe efforts to suppress these artifacts by installing a conducting electrode in front of the active area of the framing camera. This device suppresses artifacts by attracting any electrons liberated from the MCP by x-rays that arrive before the camera is triggered. Preliminary experiments indicate that it does not otherwise affect the framing camera performance.

Modeling techniques have been applied to provide further insight. We have used a suite of techniques, including electrostatic, full-wave electromagnetic, and particle-in-cell simulations to understand the fields of the entire camera and the effect of our artifact suppression system. These simulations have shown that it is important to include the effects of components other than just the microstrips and microchannel plate in the head of the framing camera to obtain accurate EM fields.

Though this artifact was first identified on experiments at NIF due to the high-intensity of x-ray flux associated with hohlraum experiments that use >1MJ of laser energy, susceptibility to this artifact is nonetheless common to all pulsed framing cameras. Moreover, the artifact is sensitive to the specific time-dependent electromagnetic field within the entire camera head, something that varies substantially from camera to camera.

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8850-19, Session 5

High-bandwidth impedance-matching circuits for National Ignition Facility gated x-ray framing cameras

Charlie S. Anderson, Joe P. Holder, Kenneth W. Piston, Natalia Simanovskaia, Gregory A. LaCaille, Perry M. Bell, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) is the largest, most energetic laser facility in the world. To date, NIF has delivered 500 TW of peak power to target. Historically, NIF has been used for inertial confinement experiments and is capable of delivering 192 laser beams to compress a small capsule housed in several different hohlraum designs. In order to quantify the physics of NIF targets several diagnostics are deployed. Gated x-ray framing cameras are a critical target diagnostic used for imaging NIF targets.

Microstripline microchannel plate (MCP) detectors are used in the gated x-ray framing cameras. In order to achieve desired time gated images, the MCP must be pulsed electrically. This pulse must be high-bandwidth and high voltage (~1000V) to achieve the temporal resolution and optimum gain from the MCP. The microstripline structures applying gating voltage to the MCP "dielectric" are low impedance (<12 ohm) devices. The high voltage pulsers and interfacing transmission line components are as implemented as "standard" 50 ohm systems. Our new cameras use either a direct mismatch or transmission line transformer as an integral part of the detector housing allowing 50 ohm vacuum interfaces. Detector assembly and impedance matching circuit designs, parameters and implementations will be discussed.

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8850-20, Session 5

Strip velocity measurements for gated x-ray imagers using short pulse lasers

Patrick W. Ross, Christopher T. Silbernagel, Michael Cardenas, Andrew S. Mead, Matthew C. Griffin, National Security Technologies, LLC (United States)

Strip velocity measurements of gated X-ray imagers using an ultra-short pulse laser are presented. Obtaining time-resolved X-ray images of inertial confinement fusion shots presents a challenge. One diagnostic developed to address this is the gated X-ray imager (GXD). The GXDs developed by Lawrence Livermore National Laboratory and Los Alamos National Laboratory use a microchannel plate (MCP) coated with a gold strip line that serves as a photocathode. GXDs are used with an array of pinholes which image onto various parts of the GXD image plane. As the pulse sweeps over the strip lines, it creates a time history of the event with consecutive images. To accurately interpret the timing of the images obtained using the GXDs, it is necessary to measure the propagation of the pulse over the strip line. The strip velocity was measured using a short pulse laser with a pulse duration of approximately 1-2 ps. The 200 nm light from the laser illuminates the GXD MCP. The laser pulse is split and a retroreflective mirror is used to delay one of the beam paths. By adjusting the distance to the mirror, one beam path is temporally delayed compared to the reference path. The retroreflective setup is calibrated using a streak camera with a 1 ns full sweep. Spatial resolution of 0.5 mm achieves a temporal resolution of ~5 ps on the GXD strip line.

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8850-21, Session 6

Engineering precision relocation capability into a large-cantilevered telescoping diagnostic

Jake M. Parker, Marion J. Ayers, Todd A. Decker, Perry M. Bell, David K. Bradley, Tommaso Pardini, Thomas J. McCarville, Paul B. Mirkarimi, Randolph M. Hill, Lawrence Livermore National Security, LLC (United States)

The Kirkpatrick Baez Optics (KBO) diagnostic used on the National Ignition Facility has defined its mirror location repeatability requirements to be within a 150 micron spherical diameter each time that it is extended along its telescoping rail path during offline alignment and during its use on the NIF. When extended, the mirrors are located at the end of a Diagnostic Load Package, cantilevered more than three meters out from its bolted connection points. Discussed are the structural challenges and the mechanical design solutions that were implemented to achieve the 150 micron location repeatability goal of the diagnostic.

8850-22, Session 6

X-ray diffraction diagnostic design for the National Ignition Facility

Maryum F. Ahmed, Lawrence Livermore National Lab. (United States) and Akima Infrastructure Services, LLC (United States); F. Allen House, Raymond F. Smith, Lawrence Livermore National Lab. (United States); Zachary Lamb, Lawrence Livermore National Lab. (United States) and Akima Infrastructure Services, LLC (United States); David W. Swift, Lawrence Livermore National Laboratory (United States)

This paper describes the design considerations for Target Diffraction In-Situ (TARDIS), an x-ray diffraction diagnostic at the National Ignition Facility. A crystal sample is ramp-compressed to pressures between 10 and 30 Mbar and flooded with x-rays from a backlighter source foil. The crystal spectrography diffraction lines are recorded onto image plates. The crystal sample, filter, and image plates are packaged into one assembly, allowing for accurate and repeatable target to image plate registration. Unconverted laser light impinges upon the device, generating debris, the effects of which have been mitigated. Dimpled plastic blast shields, high strength steel alloy, and high-z tungsten are used to shield and protect the image plates. A tapered opening was designed to provide adequate thickness of shielding materials without blocking the drive beams or x-ray source from reaching the crystal target. The high strength steel unit serves as a mount for the crystal target and x-ray source foil. A tungsten body contains the imaging components. Inside this sub-assembly, there are three image plates: a 160 degree field of view curved plate directly opposite the target opening and two flat plates for the top and bottom. A polycarbonate frame, coated with the appropriate filter material and embedded with registration features for image plate location, is inserted into the diagnostic body. The image plate assembly is metrologized and then mounted to the target assembly via a kinematic coupling. Target metrology is then performed on the integrated assembly.

8850-23, Session 6

Design of survey x-ray spectrometer for NIF "NSS"

Shannon L. Ayers, Marilyn B. Schneider, Perry M Bell, David K. Bradley, Lawrence Livermore National Lab. (United States); John F. Seely, Uri Feldman, Walter L. Marlin, Artep, Inc. (United States)

Crystal spectrometers have been used on many experiments around the world to record spectra from laser-produced plasma. The NIF Survey Spectrometer (NSS) is being developed at the National Ignition Facility to record high resolution spectra covering a large x-ray range (6keV to 150keV). The NSS diagnostic is a Cauchois spectrometer consisting of a bent crystal in transmission geometry, a slit aperture, and a detector on the Rowland Circle. Two spectrometer channels with identical optical paths allow for the modular crystal design used in this instrument. Deployment of the NSS in the NIF facility will be implemented in two phases. Phase one is use of the NSS as a DIM based diagnostic and is currently being implemented. Phase two is a planned deployment of the NSS on a fixed port in a custom manipulator.

8850-24, Session 6

Implementation of a new multiple monochromatic x-ray 2D imager at NIF

George A. Kyrala, Drew Martinson, Frank Lopez, Tom Gravlin, Randall P. Johnson, Paul Polk, Thomas J. Murphy, Mark J. Schmitt, Los Alamos National Lab. (United States); F. Allen House, Reg Wood, Lawrence Livermore National Lab. (United States); Joshua J. Lee, Michael J. Haugh, National Security Technologies, LLC (United States)

We will describe the installation and wavelength calibration of a multiple monochromatic imager to be used on mix experiments at NIF. The imager works between 8-13 keV , has a spatial resolution of 16 micrometer and generates many images each with an energy bandwidth of ~80 eV . The images are recorded either on image plates or on gated x-ray detectors. We will describe: how we aligned the instrument on the bench using visible light, how we checked the alignment and determined the energy range using a k-alpha xray source, and how we installed and aligned the instrument to the NF target chamber

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8851-1, Session 1

Sub-100-nm 3D-elemental mapping of frozen-hydrated cells using the bionanoprobe *(Invited Paper)*

Si Chen, Argonne National Lab. (United States); Ye Yuan, Northwestern Univ. (United States); Claus Flachenecker, Xradia, Inc. (United States); Junjing Deng, Rachel Mak, Tatjana Paunesku, Northwestern Univ. (United States); Qiaoling Jin, Argonne National Lab. (United States); Benjamin Hornberger, Xradia, Inc. (United States); Sophie C. Gleber, Deming Shu, Lydia Finney, Christian Roehrig, Jörg Maser, Barry Lai, Argonne National Lab. (United States); Keith Brister, Northwestern Univ. (United States); Stefan Vogt, Chris J. Jacobsen, Argonne National Lab. (United States); Gayle Woloschak, Northwestern Univ. (United States)

Hard X-ray fluorescence microscopy (XFM) is one of the most sensitive techniques to perform trace elemental analysis of biological samples, such as cells and tissues. As the spatial resolution increases beyond sub-micron scale, conventional sample preparation method, which involves dehydration, may not be sufficient for preserving subcellular structures in the context of radiation-induced artifacts. To reduce structural radiation damage, as well as allow imaging under hydrated "natural state" conditions, we have developed the Bionanoprobe (BNP), a hard X-ray fluorescence nanoprobe with cryogenic capabilities, dedicated to studying trace elements in frozen-hydrated biological systems. The BNP is installed at an undulator beamline at Life Sciences Collaboration Access Team at the Advanced Photon Source. It provides a spatial resolution of 30 nm for fluorescence imaging by using Fresnel zone plates as nanofocusing optics. Differential phase contrast imaging is carried out at the same time by using a quadrant photodiode mounted downstream of the sample. By employing a liquid-nitrogen-cooled sample stage and cryo specimen transfer mechanism, the samples are well maintained below 110 K during both transfer and X-ray imaging. The BNP is capable for automated tomographic dataset collection, which allows visualizing 3D distributions of elements inside the sample. In this presentation, we will describe the instrument design principles, quantify instrument performance, and report the early results obtained with the BNP from frozen-hydrated whole cells.

8851-2, Session 1

The CNM/APS hard x-ray nanoprobe: upgrades and current performance

Ian McNulty, Robert P. Winarski, Martin V. Holt, Volker Rose, Peter Fuesz, Argonne National Lab. (United States)

The Hard X-ray Nanoprobe at the Argonne Center for Nanoscale Materials and Advanced Photon Source is a precision platform for scanning probe and full-field microscopy with 8-12 keV x-rays at 30 nm spatial resolution [1]. This multimodel microscope is capable of scanning fluorescence, diffraction, and nanotomographic imaging experiments. The Nanoprobe position sensing and stabilization system was recently upgraded to a more compact and robust fiber-guided single-bounce laser interferometer that provides 50 nm position stability between the focusing optics and sample stage over periods exceeding 8 hours, with a travel range greater than 10 mm in all three axes. Other major upgrades to the Nanoprobe include a temperature controlled sample stage for in-situ measurements at cryogenic and high temperatures, and an integrated stage for combined scanning and tomographic imaging. In future, new nanofocusing optics with higher resolution (20 nm) and greater efficiency (5%) will be implemented. This talk discusses these upgrades and the current performance of the instrument with recent applications in nanoscience.

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8851-3, Session 1

Status of the Nanoscopium scanning nanoprobe beamline of Synchrotron Soleil

Andrea Somogyi, Kadda Medjoubi, Cameron M. Kewish, Vincent Leroux, Marc Ribbens, François A. Polack, Jean-Pierre Samama, Synchrotron SOLEIL (France)

The Nanoscopium1,2 155 m-long scanning nanoprobe beamline of Synchrotron Soleil (St Aubin, France) is dedicated to quantitative multi-modal imaging in the 5-20 keV energy range. Two experimental stations, working in consecutive operation mode, will provide coherent scatter imaging and spectro-microscopy techniques for various user communities. Both continuous fast scanning3 with millisecond dwell times and nm precision step-scan mode operation will be provided for multiscale imaging; that is imaging large fields of view with moderate spatial resolution and sensitivity, followed by high spatial resolution and high sensitivity mapping of small volumes of interest. Next to fast scanning, cryogenic cooling will also reduce the radiation damage of sensitive samples during a measurement. Nanoscopium is in the construction phase, the first user experiments are expected in 2014. The main characteristics of the beamline and an overview of its status will be given in this contribution.

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8851-4, Session 1

Optical performances and nanoprobe design of the NSLS-II SRX beamline

Vincent de Andrade, Juergen Thieme, Oleg Chubar, Yuan Yao, Brookhaven National Lab. (United States)

The Sub-micron Resolution X-ray spectroscopy beamline (SRX) is one of the seven project beamlines of NSLS-II at Brookhaven National Laboratory. SRX (ΔE: 4.65-23 keV) will address a wide variety of scientific applications probing heterogeneous complex systems from the meso to the nanoscale. Combined with state of the art optics, the ultralow emittance and stability of the NSLS-II source is particularly suitable for nanoprobes. The SRX main optical components consist of a horizontally focusing mirror creating a secondary source whose size is adjustable with slits, an ultra-stable horizontally deflecting monochromator and two sets of Kirkpatrick-Baez mirrors in two inline stations as focusing optics for operations requiring either high flux or high resolution. The presentation will focus first on the beamline layout that has been optimized with FEA, ray-tracing and wave front propagation simulations using respectively Shadow and SRW. The effects of partial coherence and the impact of the KB mirrors length (in contrast with thin lenses) were successfully modeled with the last SRW add-ons. Results demonstrate that the micro and nanoprobes will provide 1013 and 1012 ph/s respectively in a sub-micron

and a 50 nanometer spot, with an excellent energy resolution (close to the Darwin width of the selected crystals). At last, the nanoprobe design will be described in detail, with a highlight on interferometry tests performed on various sample stage assemblies that conducted our choices.

8851-5, Session 1

A next-generation in-situ nanoprobe beamline for the Advanced Photon Source

Jörg Maser, Barry Lai, Argonne National Lab. (United States); Tonio Buonassisi, Massachusetts Institute of Technology (United States); Zhonghou Cai, Si Chen, Lydia Finney, Sophie C. Gleber, Chris J. Jacobsen, Argonne National Lab. (United States); Conal Murray, IBM Thomas J. Watson Research Ctr. (United States); Curt A. Preissner, Deming Shu, David J. Vine, Stefan Vogt, Argonne National Lab. (United States)

The Advanced Photon Source is currently developing a suite of new hard x-ray beamlines, aimed primarily at the study of materials and devices under real conditions. One of the flagship beamlines of the APS Upgrade is the In-Situ Nanoprobe beamline (ISN beamline), which will provide in-situ and operando characterization of advanced energy materials and devices under change of temperature and gases, under applied fields, in 3D.

The ISN beamline is designed to deliver spatially coherent x-rays with photon energies between 4 keV and 30 keV to the ISN instrument. As an x-ray source, a revolver-type undulator with two interchangeable magnetic structures, optimized to provide high brilliance throughout the range of photon energies of 4 keV – 30 beamline, will be used. The ISN instrument will provide a smallest hard x-ray spot of 20 nm using diffractive optics, with sensitivity to sub-10 nm sample structures using coherent diffraction. Using nanofocusing mirrors in Kirckpatrick-Baez geometry, the ISN will also provide a focus of 50 nm with a flux of 8·1011 Photons/s at a photon energy of 10 keV, several orders of magnitude larger than what is currently available. This will allow imaging of trace amounts of most elements in the periodic system, with a sensitivity to well below 100 atoms for most metals in thin samples. It will also enable nano-spectroscopic studies of the chemical state of most materials relevant to energy science. We will discuss the beamline design, and discuss initial studies related to the science thrust of the ISN beamline.

8851-6, Session 2

Development of full-field hard x-ray microscopy with four aspherical mirrors

(Invited Paper)

Satoshi Matsuyama, Yoji Emi, Osaka Univ. (Japan); Yoshiki Kohmura, Kenji Tamasaku, Makina Yabashi, Tetsuya Ishikawa, RIKEN (Japan); Kazuto Yamauchi, Osaka Univ. (Japan)

We developed achromatic full-field hard X-ray microscopy on the basis of advanced Kirkpatrick-Baez (KB) mirrors consisting of four total-reflection mirrors. A designed optical system has 210x and 385x magnifications in vertical and horizontal directions, 0.0012 of numerical apertures in both directions and the working distance of 50 mm. Two elliptical mirrors and two hyperbolic mirrors with a figure accuracy of 2 nm were fabricated using elastic emission machining (EEM), microstitching interferometry (MSI) and relative-angle-determinable stitching interferometry (RADSI). We constructed an imaging system for magnifying transmission X-rays through a sample between the first and third experimental hutches of BL29XUL (SPring-8) to check the performance. A monochromatized X-ray of 10 keV was focused at the object plane using KB mirrors as a condenser. The transmission X-ray through the sample was collected by the advanced KB mirrors. The sample used was a Siemens star chart with a minimum resolution of 50 nm. Finally, a magnified image was formed at an X-ray CCD system placed ~45 m downstream of the objective. As a result, an X-ray image with a spatial resolution of ~150 nm was acquired. Also, no chromatic aberration was confirmed by taking images at an X-ray energy from 8 to 11.5 keV.

8851-7, Session 2

Efficient full-field x-ray microscopy with Zernike phase contrast having suppressed halo at Petra III

Ismo J. Vartiainen, Christian David, Paul Scherrer Institut (Switzerland); Alke F. Meents, DESY (Germany)

Imaging with multi-keV X-rays can reveal new nanoscale structural information even from thick specimens. However, due to a large penetration depth of X-rays, the absorption contrast is low especially when imaging biological samples. The contrast can be greatly enhanced similarly to the case of the visible light by applying phase contrast technique invented by Zernike. We report on the implementation of a full field X-ray microscope using Zernike phase contrast at 6.2keV at Petra III P11 in DESY Hamburg. The setup is well suited for high resolution imaging of samples that have low absorption contrast. Illumination of the sample is optimized by using a beam shaper as a condenser lens. This scheme enables uniform illumination over the FOV without scanning the optics. Illumination based on a beam shaper is very photon efficient compared to a classical hollow cone illumination as the whole incident beam can be exploited. Moreover, we show how the halo artifacts, often encountered in Zernike phase contrast can be suppressed by an optimized design. We present the first experimental results in phase and absorption contrast. In addition, quantitative phase imaging based on phase subtraction will be discussed.

8851-8, Session 2

Development of large-field high-resolution hard x-ray imaging microscopy with Fresnel zone plate objective

Yoshio Suzuki, Akihisa Takeuchi, Yasuko Terada, Kentaro Uesugi, Japan Synchrotron Radiation Research Institute (Japan)

Spatial resolution of hard x-ray imaging microscopy is now below 100 nm using Fresnel zone plate (FZP) objective lens. However, for practical use, large field of view (FOV) and high throughput are as important as the spatial resolution. The FOV of FZP microscope is restricted by the physical diameter of the objective FZP, and x-ray imaging detectors with high spatial resolution and high efficiency are very difficult at present. Therefore, a simple solution for the large-FOV high-resolution high-throughput x-ray microscopy is achieving large magnification by expanding the length of microscope system using a long experimental station. The beamline 37XU of SPring-8 was recently modified, and it is capable to construct very long (~30 m long) microscope system by combining three experimental hitches. Some configurations of microscope systems were tested. In a typical condition, a magnification of 133 and a FOV of 123 µm are attained using a FZP with a diameter of 310 µm and an outermost zone width of 100 nm. In this case, the effective pixel size is 60 nm. Spatial resolution was also evaluated by observing resolution test chart, and the spatial resolution of about 180 nm in full pitch of periodic object is achieved with an exposure time of 1 s. When a FZP with 50 nm outermost zone width, FOV of 50 µm and spatial resolution better than 100 nm are also achieved with an exposure time of 4 s. Three dimensional measurement by CT technique is also being carried out.

8851-9, Session 3

5D visualization of phase transitions *(Invited Paper)*

Yijin Liu, SLAC National Accelerator Lab. (United States); Junyue Wang, Carnegie Institution (United States); Wendy L. Mao, Stanford Univ. (United States); Wenge Yang, Carnegie Institution (United States)

The most substantial advancements in X-ray imaging techniques in the past decades are closely related to the availability of the synchrotrons and the development of advanced X-ray optics. The combination of the X-ray energy scanning and the full-field imaging technique has been demonstrated and recognized as a powerful tool for materials science studies. This functionality provides significant additional chemical information to the 3D geometry of the sample which is available through conventional imaging techniques. Utilizing to this newly developed imaging technique and a specially designed Diamond Anvil Cell pressure vessel, we investigated the pressure induced phase transition in BiNiO3 and present FIVE dimensional (X, Y, Z, Energy, Pressure) visualization, which is the morphology and chemical distribution change as a function of external pressure. We expect the presented method have significant impact in the application of X-ray imaging in materials science.

8851-10, Session 3

In-situ TXM of dynamic electrochemical systems

Johanna L. Nelson, Joy C. Andrews, Michael F. Toney, SLAC National Accelerator Lab. (United States)

Benefiting from the penetrating power, long focal length, and large depth of focus of transmission (hard) X-ray microscopy (TXM), we have developed a robust experimental program of in situ imaging. High resolution, in situ microscopy allows the visualization of dynamic systems in time, capturing a wealth of information inaccessible to ex situ imaging methods.

A global shift towards clean, renewable energy relies on the availability of cheap, high capacity, and high power energy storage devices. Li-ion batteries show promise as a clean alternative to the internal combustion engine; however, setbacks such as capacity fading hinder the full capability of these rechargeable batteries. With in situ TXM we can track the morphological changes of electrode material within operating Li-ion batteries such as the high capacity Li-S [1] and Li-Ge systems. By studying Li-ion batteries in situ we can better understand their electrochemical dynamics and failure mechanisms.

ZnO holds great promise for the development of low-cost electronic and photonic devices such as sensors, solar cells and light-emitting diodes because of its unique electrical, optoelectronic and luminescent properties. Using electrodeposition, ZnO nanostructures can be synthesized cheaply and the morphology can be precisely tuned by controlling deposition conditions (temperature, applied potential, time, and chemical composition of the deposition bath). By imaging this system in situ we can better understand the nucleation and growth of these nanostructures, which directly affect the properties of the final structure.

[1] J. Nelson et al. JACS 2012

8851-11, Session 3

Development of in-situ full-field spectroscopic imaging analysis and application on Li-ion battery using transmission x-ray microscopy

Yu-Chen K. Chen-Wiegart, Jiajun Wang, Jun Wang, Brookhaven National Lab. (United States)

Transmission x-ray microscopy (TXM), a full-field x-ray imaging method, can provide sub-30 nm spatial resolution with hard x-ray. In addition to observing morphology, TXM can also provide elemental and chemical information via spectroscopic imaging. A newly developed TXM at beamline X8C of National Synchrotron Light Source has brought new capabilities. One of them is motorizing the detector along x-ray beam direction to provide a fixed magnification and therefore to utilize the best resolution of the instrument during spectroscopic imaging. With this new feature, we advanced in experimental method and image analysis to conduct TXM spectroscopic imaging in an in situ fashion. First, by tuning the incident x-ray energy, we obtain a series of energy-dependent full field images where each pixel (~10-40 nm in size) contains a full X-ray Absorption Near Edge Structure spectrum. By performing least-squares linear combination fitting on each pixel, the full-field imaging provides the capability to reveal the chemical state distribution within the sample. Then by conducting in situ imaging during a chemical/electrochemical reaction, a time-dependent and spatially resolved composition mapping series can be obtained. Coupling with the morphology observed during in situ imaging, we can correlate the reaction conditions, chemical states distribution change, and morphological evolution within the sample. We successfully applied this method to study the electrochemical evolution of CuO, an anode material of Li-ion battery, during the lithiation-delitiation cyling. This in situ TXM spectroscopic imaging can also be applied to other functional and energy storage materials where morphological and reduction-oxidation together play critical roles.

8851-12, Session 3

Development of in-line furnace for in-situ high-resolution x-ray microscopy

Christopher Eng, Yu-Chen K. Chen-Wiegart, Jun Wang, Brookhaven National Lab. (United States)

Full field transmission x-ray microscopy (TXM) is a newly developed x-ray imaging technique to provide quantitative and non-destructive 3D characterization of the complex microstructure of materials at nanometer resolution. A key missing component is an in situ apparatus enabling the imaging of the complex structural evolution of the materials and to correlate the structural change with a material's functionality under real operating conditions. This work describes the design of an environmental cell which satisfies the requirements for in situ TXM studies. The limited space within the TXM presents a spatial constraint which prohibits the use of conventional heaters, as well as requiring consideration in designing for safe and controlled operation of the system and alignment of the cell with the beam. A gravity drip-fed water cooling jacket was installed in place around the heating module to maintain critical components of the microscope at safe operating temperatures. A motion control system consisting of pulse width modulated DC motor driven XYZ translation stages was developed to facilitate fine alignment of the cell. Temperature of the sample can be controlled remotely and accurately through a controller to temperatures as high as 1200K. Heating zone measurement was carried out and shows a 500 x 500 x 500 µm3 homogeneous zone volume for sample area, which is a critical parameter to ensure accurate observation of structural evolution at nanometer scale with a sample in size of tens of microns. Application on Ni particles for in-situ oxidation experiment is also discussed.

8851-13, Session 4

High-resolution high-aspect ratio zone plate fabrication

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We have developed a method to fabricate high aspect ratio, dense Si structures required for high resolution, high efficiency x-ray diffractive optics. This method utilizes metal assisted chemical etching and requires

only a single lithographic patterning step and a single pattern etching step. It is scalable to large-area features (larger diameter zone plates), and is compatible with programmable patterning (variations on zone plate structure), basic mechanical stacking, and metallization techniques such as atomic layer deposition or electroplating. Fabrication of very high aspect ratio structures exhibiting smooth sidewalls has been achieved at 1:50 aspect ratio for 50 nm half period structures. This fabrication method is a simple route to creating high resolution, high aspect ratio diffractive optics for various x-ray sources.

8851-14, Session 4

Deposition of elliptical-shaped KB mirrors for ESRF microfocus beamline ID13

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A pair of Platinum coated Kirkpatrick-Baez (KB) mirrors, a 40 mm long vertical focusing mirror (VF) and a 25 mm long horizontal focusing mirror (HF), was fabricated for the microfocus beamline ID13 at European Synchrotron Radiation Facility (ESRF) using magnetron sputtering technique. They were designed to achieve a focal spot size ≤ 150 x 150 nm2. Specially designed spherically shaped silicon substrates with were achieved to fit the compact KB system developed by the ESRF. For all of the previous KB mirrors that were fabricated using the profile coating method, typically two to more deposition steps are required. However, both of the two mirrors used just one deposition step and the surface figure (height) errors are 0.43 nm (VF) and 0.37 nm (HF) from the metrology measurements at Advanced Photon Source (APS). The metrology measurements from ESRF matched with APS's metrology results and also gave the rms slope errors of the two mirrors of 0.27 µrad (VF) and 0.25 ?rad (HF). The detailed fabrication process and the metrology measurement results of these mirrors are introduced in this paper. Preliminary beamline test results showed that the mirror pair achieved the design goal [1].

References:

[1] R. Barrett, B. Shi, A. Vivo, R. Baker, L. Assoufid, "Compact Kirkpatrick-Baez focusing system with profile-coated, elliptically-figured mirrors," SRI, Lyon, France, 2012.

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8851-15, Session 4

Design optimization of ultra-precise elliptical mirrors for hard x-ray nanofocusing at Nanoscopium

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The design and implementation of a pair of 100 mm-long grazing-incidence total-reflection mirrors for the hard X-ray beamline Nanoscopium [1] at Synchrotron Soleil is presented. A vertically and horizontally nanofocusing mirror pair, oriented in Kirkpatrick-Baez geometry have been designed and fabricated using deterministic polishing, with the aim of creating a diffraction-limited high-intensity 5-20 keV beam with a focal spot size as small as 50 nm (full-width at half-maximum, FWHM). We describe the design considerations, including wave-optical calculations [2] of figures-of-merit that are relevant for spectromicroscopy, including the focal spot size, depth of field and integrated intensity. The mechanical positioning tolerance in the pitch angle that is required to avoid introducing high-intensity features in the neighborhood of the focal spot is demonstrated with simulations to be of the order of microradians, becoming tighter for shorter focal lengths and therefore directly affecting all nanoprobe mirror systems. Metrology results for the completed mirrors are presented, showing that better than 2 Å-rms figure error over spatial frequency bandwidths from 100 µm to full substrate length (and in the sub-100µm regime better than 1 Å-rms) has been achieved, with respect to the designed elliptical surfaces, with less than 61 nrad-rms slope errors.

References

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[2] Kewish, C. M., Assoufid, L., Macrander, A. T., and Qian, J., "Wave-optical simulation of hard-X-ray nanofocusing by precisely figured elliptical mirrors," Appl. Opt. 46, 2010-2021 (2007).

8851-16, Session 5

Focus characterization of multilayer Laue lens using phase retrieval

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It is of critical importance to quantitatively characterize the performance of X-ray optics, when advanced X-ray lenses can produce focal sizes to sub-10 nm range. Ptychography, a phase-retrieval based method, is capable to reconstruct the complex-valued wavefront of X-ray beam, thus provide precisely characterization of lenses. We designed and built a dedicated instrument for ptychographical measurement of Multilayer Laue Lens (MLL). The X-ray wavefront focused by a MLL with 43 micron aperture and 4.2 mm focal length was successfully reconstructed from experimental data. 12 nm line focus was obtained. This method will be matured as a characterization tool to examine MLL lenses fabricated under various conditions for the purpose of rational optimization of fabrication process.

8851-17, Session 5

Ronchi interferometry for characterization of nanofocusing hard x-ray optics

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Hard x-ray nanobeams have become an important tool in modern synchrotron radiation research. These nanobeams are usually created by focusing undulator radiation with highly specialized nanofocusing optics like reflective Kirkpatrick-Beaz mirror systems, diffractive zone plates or refractive compound lenses to focal spot sizes below 100 nm in diameter. The optics should in the best case not introduce any aberrations into the wavefield to ensure diffraction-limited focusing performance, and therefore the characterization of the hard x-ray nanobeam behind the focusing optic has become an important issue. We have introduced a classical scheme for this task, the so-called Ronchi test. A periodic pattern, normally a grating, is placed close to the focal plane of an optical system, and a detector is placed at a certain distance behind. The different diffraction orders of the grating can then interfere with each other, giving rise to a characteristic fringe pattern that can be evaluated to obtain information about the quality of the wavefront. Although well-known from visible optical metrology, it has not been applied for hard x-ray radiation. We believe that this test could offer a number of advantages compared to existing methods for hard x-ray beam

characterization. We will present results from experiments with both diffractive and refractive nanofocusing optics and using synchrotron as well as free electron laser radiation. We will show that the Ronchi method is simple to implement and can, in the case of free electron laser, provide single-shot information about focusing quality.

8851-34, Session PWed

High-efficiency x-ray nanofocusing using the kinoform stacking of binary zone plates

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The efficiency of binary Fresnel zone plate lens is limited by the fact that they have equally strong positive and negative diffraction orders. To surpass this limitation, a kinoform lens profile is required. The multi-step approximation of this profile can be achieved by several aligned layers of fabrication. This approach is very challenging for small zone width and high photon energies, where high zone structures are required. Here we demonstrate an alternative method by the stacking of two binary zone plates in each others near-field to produce an effective 4-step profile. By using a “coarse” zone plate with giving a π phase shift and a “fine” zone plate with double line density giving a $\pi/2$ phase shift, theoretical diffraction efficiency up to 71% can be obtained for nickel zone structures at 6.5 keV photon energy. This is almost twice the value of the corresponding binary zone plate. The approach has been verified using a compact experimental setup based on piezo actuators for fine alignment. For a zone plate pair with 500 µm diameter and 200 nm effective outermost zone widths, we measured a diffraction efficiency of 47.1%, which is clearly beyond the limitations of binary zone plates. This zone plate is meant to provide high intensity illumination for ptychographic experiments at the Nanoscopium beamline of the synchrotron SOLEIL.

8851-35, Session PWed

Recent developments in cryogenic synchrotron and laboratory x-ray microscopy

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For specimens from the life sciences like cells and tissue, cryogenic sample handling is essential for limiting the effects of radiation damage and preservation of the sample structure when imaging at high resolution (tens of nanometers). We present here recent instrumentation developments and initial experimental results of a new suite of cryogenic x-ray microscopes.

A full-field microscope operating in the water window range (280 to 540 eV) has been developed for cryogenic tomographic imaging of individual cells or similar specimens. The microscope can operate at a synchrotron beamline as well as with a laboratory soft x-ray source. Tomographic images of frozen hydrated yeast at about 40 nm resolution, obtained with a nitrogen plasma laboratory source operating at 430 eV, will be presented. A hard x-ray version operating from 5 to 11 keV for imaging of tissue sections and other thicker specimens is currently in commissioning. Furthermore, a scanning nanoprobe has been developed for trace element mapping in frozen hydrated life science samples. It operates in the 5 to 20 keV energy range at a resolution down to 30 nm.

All instruments described here share a common cryogenic sample handling system based on cartridges that allow offline sample preparation with subsequent sample transfer into the microscope under cryogenic conditions and robotic sample exchange inside the microscope. The system further allows cryogenic sample transfer to other instruments like cryogenic light or electron microscopes for imaging of the same specimen with different methodologies, correlating for example structure and function.

8851-36, Session PWed

Development of a high-resolution imaging system at the Polish Synchrotron

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This presentation will describe our work towards a new high resolution imaging system considered for the Polish Synchrotron SOLARIS in Krakow, Poland. The inspiration for this development derives from earlier research projects covering two fields:

A. Development of high resolution the photo electron emission microscopy (PEEM) systems where resolution down to 2 nm has been already achieved. To follow this direction it is necessary to develop and apply in the system a highly efficient materials for secondary electron emission (SEE).

B. Investigation of new materials with high SEE. The SEE yield of heterostructures of ZnO nanoneedles coaxially coated with AlN or GaN has been studied for the first time using electron, ion, and X-ray beams. The SEE yield of the heterostructures is enhanced significantly by the intrinsic nanostructure of the ZnO nanoneedle templates as compared to the AlN and GaN thin films on Si substrates.

Combination of these two projects will allow development of a high resolution imaging system (with resolution down to 50 nm) with reduced cost when compared with traditional X-ray imaging systems. A 300 nm spatial resolution has already been demonstrated by several groups. Details of the project will be presented at the conference.

8851-37, Session PWed

Analysis of impact of sintering temperature on microstructure of LSCF-SDC composite cathodes using nano-CT

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Composites of La0.4Sr0.6Co0.8Fe0.2O3Nd (LSCF) with samarium doped ceria (SDC) has been extensively used as cathodes for solid oxide fuel cells (SOFCs) to lower its operation temperature. The ability to visualize three-dimensional (3D) microstructural changes in LSCF-SDC composite cathodes caused by processing can help elucidate the impact of microstructure on cathode performance. This study reports that we utilize the nano-computed tomography (nano-CT) technique to image the 3D microstructures of La0.4Sr0.6Co0.2Fe0.8O3 (LSCF) - Ce0.8Sm0.2O1.9 (SDC) composite cathodes which were sintering at 800, 1000, and 1200°C, respectively, for 2 h based on the Fe K-absorption edge. Using the reconstructions of LSFC-SDC composite cathodes submitted to different temperatures, the key microstructural properties, such as volume fraction of each phase, connected volume fraction, surface area, triple-phase boundary length, and pore size were measured. The effect of sintering temperature on the microstructure of LSFC-SDC cathodes was discussed and compared with theoretical simulation. With increasing sintering temperature in the range from 800 to 1200oC LSFC-SDC composite cathode microstructure was found that the volume fraction and grain size of LSCF material increased, while the volume fraction of SDC decreased. Furthermore, the triple-phase boundary length per volume increased as the sintering temperature increasing, which is consistent with the theoretical simulation data from previous literature1. This study had revealed that the nano-CT can provide a powerful tool to investigate the 3D microstructure of energy materials and optimize its preparation condition to gain better functional performance.

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8851-38, Session PWed

Reconstruction of yeast cells imaging using algebraic reconstruction technique

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Full-field hard X-ray tomography based on Fresnel zone-plates has been applied to obtain nanoscale internal-structures of biological samples. The imaging of the yeast based on Zernike phase contrast imaging technique and heavy metal staining method has better contrast than that based on absorption imaging. Generally, there are two key aspects influencing the sufficiency of projections of biological samples for precise image reconstruction. One is that the maximum rotation angle of the sample stage has been limited for yeast imaging. The other is that long time imaging may cause the serious environmental noise pollution which would reduce the quality of the projection image. In condition that the projection data is insufficient, Algebraic Reconstruction Technique (ART) is the better choice than Filtered Back Projection (FBP). The ART would obtain a better spatial resolution of the reconstructed image. It is also possible to incorporate some types of priori knowledge about the image into the solution to improve the robustness of the algorithm proposed and speed up the convergence. In this work we applied the ART to numerical demonstration and the reconstruction of yeast cells. Different parameters were used for the ART to obtain a better result. The results show ART is a suitable tool for reconstructing the insufficient projection data.

8851-39, Session PWed

A LabVIEW-based nano-CT image alignment software platform

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As a uniquely non-destructive high resolution visualization tool, X-ray nanometer computed tomography (nano-CT) has been found wide application in scientific research and industrial area. However in practical experiment, because of the mechanical vibration and thermal expansion, the rotation axis of the sample room would always jitter during its rotating procedure, which would cause blurring and additional streaking artifacts in 3D reconstruction if without an accurate calibration of the center of rotation. Here based on National Instrument's Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW), by means of gray value barycenter and circle fitting method, the gold particles acting as the reference point in each projective image would be automatically detected, after relevant adjustment in horizontal and vertical direction, almost no artifacts in latter 3D reconstruction exist. This nano-CT image alignment software platform dedicated for nano-CT equipment at Beijing Synchrotron Radiation Facility (BSRF) facilitates users during their experiments.

8851-41, Session PWed

Quantitative data from in-line phase contrast: analytical phase-retrieval methods

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In-line phase-contrast x-ray imaging is a method readily used for obtaining phase information, but the generation of quantitative data requires phase retrieval. We identify and analyze the seven existing analytical approaches, and integrate those into a single method [1]. Each method is then presented as a variation of this unified method, and a scheme for choosing a relevant phase-retrieval method presented.

Using in-line phase-contrast imaging, edge-amplified images are obtained. The edges of a sample are clearly shown, and the images provide excellent data on, e.g., the presence or location of an object. But for quantitative data, such as the thickness of an object, and for tomographic reconstruction and surface rendering, the raw data must be processed to reconstruct the object. This procedure is phase retrieval, and can be done analytically or iteratively.

Concentrating on the analytical methods for speed and simplicity, and considering only the single-distance setup, we identify seven existing approaches, show that these methods all follow the same pattern, and present them as a unified method. The different approaches are separated by differences in specific steps of the methods. We also outline the assumptions and approximations of those approaches and from that information can provide a simple scheme for choosing the correct phase-retrieval approach in a specific situation. Examples of phase retrieval for biological or material samples are presented.

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8851-42, Session PWed

Conceptual design for the hard x-ray nanoprobe beamline at the SSRF

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The hard X-ray nanoprobe beamline (HXN) planned at Shanghai Synchrotron Radiation facility (SSRF) will be of capability to realize a focal spot size of below 30 nm for hard X-rays to satisfy urgent requirements in material, biology, environment sciences and etc. The cryogenic permanent magnet undulators (CPMU18) will be selected and cover the energy range of 5-30 KeV. A plane mirror will be put in front of monochromator to decrease heat load and a toroidal mirror in front of secondary slit to realize pre-focusing. The beamline includes two modes of operation, high flux mode and high energy resolution mode respectively. High flux mode is based on a double multilayer monochromator (DMM) and a multilayer-based Kirkpatrick-Baez mirror system, which can obtain 4E+9 photons/s flux at the sample position at 15 KeV. A pair of Montel nested multilayer-based K-B mirror with Pt/C periodic structure can afford large numerical aperture and enough working space. By precise mechanical control and wavefront correction, it is possible for focusing beam to reach down to 30 nm and even to 10 nm. This mode will offer high flux for elemental mapping at low concentration. A double crystal monochromator (DCM) serves for high energy resolution mode to obtain energy resolution ($\Delta E/E$) of 2E-4. Multilayer Laue lens or transmission zone plate of large diameter is planned to focus X-rays to 30 nm with 4E+8 photons/s flux at the sample position at 10keV. The second mode will mainly be used for XANES and diffraction applications in nanoscale.

8851-43, Session PWed

A soft x-ray beamline for quantitative nanotomography using ptychography

Grant A. van Riessen, La Trobe Univ. (Australia); Mark Junker, La Trobe Univ. (Australia) and ARC Ctr. of Excellence for Coherent X-Ray Science (Australia); Bruce Cowie, Australian Synchrotron (Australia); Andrew G. Peele, La Trobe Univ. (Australia) and Australian Synchtron (Australia)

Soft X-ray nanotomography using ptychographic coherent diffractive imaging allows quantitative imaging of the internal structure of biological and materials samples with high sensitivity. In this work, we describe the experimental development of soft X-ray nanotomography at the Australian Synchrotron. An undulator beamline provides a highly coherent X-ray beam of variable polarization over an energy range 200 to 2000 eV. Illumination of the sample with a divergent beam produced using a zone plate provides a pathway to improving X-ray dose efficiency and the reliability of recovering images from diffraction data. However, this demands nanometre stability between the sample and optics, which is achieved using an interferometric metrology system. Data from characterisation studies and recent experiments are presented to illustrate the potential for fast, highly dose efficient nanotomography.

8851-44, Session PWed

Nanoparticle assembly local order characterization by angular correlation analysis of soft x-ray coherent scattering patterns

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Materials that lack long range translational order present a substantial difficulty for characterizing their “atomistic” structure. As a result, property-to-structure relation for glasses, gels, foams or colloidal crystals are not well established. Coherent x-ray scattering speckle pattern uniquely defines a spatial distribution of scatters and the recent development of coherent diffraction imaging (CDI) is meant to be a route for reconstruction of their spatial distribution. Unfortunately, even with the development of ptychography -- a robust image reconstruction technique not limited by isolated specimen requirement or a priori knowledge of incident illumination -- real experiments often fail, especially when only incomplete (with missing portion of Q space) or noisy data set are available. If one is primarily interested in symmetry of scatters local arrangement, a full CDI inversion is not needed and parameters of hidden structural ordering can be revealed by employing x-ray cross-correlation analysis (XCCA) directly to the speckle map (1). Smaller spot size (fewer effective scatters probed) help to divulge distinct angular correlation even for a disordered structures, where a raster scanning provide needed statistical averaging over the large ensemble. As XCCA is done on a point-by-point basis, the spatial distribution of particular structural motif can be mapped this way. Alternatively, one can measure a decrease of angular correlation XCCA as probe size increases (as in fluctuation microscopy (2)) to extract the spatial extent (correlation length) of distinct structural motifs for a given specimen point. Using a dense nano-particle 2D assembly, as a model system, we present and discuss experimental results stressing advantage and practical limitations of XCCA approach to accurate and systematic characterization of disorder systems.

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8851-45, Session PWed

Recent advances in use of atomic layer deposition and focused ion beams for fabrication of Fresnel zone plates for hard x-rays

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Developments and advances in e-beam lithography (EBL) made it possible to reach resolutions in a single digit nanometer range in the soft x-ray microscopy using Fresnel Zone Plates. However, it is very difficult to fabricate efficient Fresnel zone plates for hard x-rays via this conventional fabrication technique due to limitations in the achievable aspect ratios. Alternative focusing methods such as MLL and K-B mirrors also showed remarkable advances, although 2-D imaging in the real space remains to be demonstrated . Recently, we have been working on a couple of alternative methods. In one method, we fabricate a multilayer type FZP via atomic layer deposition (ALD) followed by focused ion beam (FIB) machining. In this method a ML-FZP with very high aspect ratio can be fabricated from a wide variety of materials. We already demonstrated diffraction efficiencies up to >15 % at 8 keV as well as both direct and indirect estimation of resolutions down to 30 nm. Some future projections in terms of available materials and target resolutions regarding this method will be discussed. In an other approach, we demonstrated previously, that a FZP can be fabricated easily in a single step, via ion beam lithography (IBL). Such IBL-FZPs were already successfully employed in the soft X-ray range enabling higher order imaging. Here, we show and discuss how this new method may be extended to the fabrication of Fresnel zone plates for hard X-ray range.

8851-46, Session PWed

Simplicity from complexity: Non-negative matrix analysis applied to x-ray spectromicroscopy

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In a sample containing mixed chemical states, it is important to be able to correctly identify the individual spectral components in order to characterize the chemical structure and composition of the sample, with applications such as environmental remediation and understanding biological complexes. Using data from x-ray spectromicroscopy, where an optical density (or transmission) spectrum is obtained at each pixel, principal component analysis can be used to reduce the dimensionality of the dataset and provide an orthogonal basis of abstract components which describes the variability in the data; these results can be complemented with cluster analysis to identify more realistic (rather than abstract) spectra.

However, given an optical density spectrum, which is a product of the absorption of each component and its corresponding thickness, the above methods may sometimes reconstruct negative thickness regions in the sample. To eliminate this non-physical result, we employ the method of non-negative matrix approximation (NNMA), which imposes a non-negative constraint on the reconstructed spectra and thicknesses. NNMA takes two initially random factor matrices, representing the component spectra and their thicknesses respectively, and uses iterative gradient descent until their product converge with the observed optical density within some set tolerance measured by the minimization of a cost function. Additional constraints may be added to the cost function, such as imposing smoothness to improve spectra reconstruction. It can also be shown that correctly constraining the sparseness of the thickness matrix can lead to an improvement in the speed and quality, as well as accuracy, of the spectra reconstruction.

8851-47, Session PWed

Parallel high-resolution x-ray imaging

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Many x-ray optical element (refractive, as compound refractive and kinoform lenses or diffractive - zone plates) that pushed imaging below 100nm spatial resolution is produced using microfabrication technology and their production can be scaled from single element to a fabrication of x-ray optical array. When combined with 2D x-ray detection, such approach leads to a development of novel concept of x-ray imaging, particular useful for measurements of extended objects, such as medical and biological specimens or industrial components (MEMS devices, ??) on conventional x-ray sources at spatial resolution previously not achieved. Following we report first measurements using x4 ZP array on a scanning x-ray microscope outfitted with x-ray CCD and discuss advantages and limitations of x-ray parallel imaging.

8851-48, Session PWed

Endstation development for the HXN nanoprobe at the NSLS-II

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In this work we present our approach to develop a scanning microscope for x-ray imaging in the hard x-ray regime. We implement two types of nanofocusing optics e.g. Fresnel zoneplates and Multilayer Laue Lenses to achieve nanoscale imaging. Fresnel zoneplates will enable imaging with the spatial resolution down to 30 nm and Multilayer Laue Lenses will be used to perform nanofocusing down to 10 nm respectively. Two individual modules will accommodate different types of nanofocusing optics; they can be moved and swapped inside the vacuum chamber without interference. In addition, temperature regulation of the sample in the range between 85 and 1000 K will enable phase transition studies in materials science and condensed matter physics experiments. Novel approach which includes modular design, state-of-the-art fiber optic interferometry and compact, high stiffness piezo-based positioners will be discussed. Extensive R&D work has been performed to thoroughly evaluate and characterize individual components integrated into a microscope. We present preliminary results for resolution, thermal stability and vibrations characteristics for the prototype module equipped with the Multilayer Laue Lenses. Sub-nm sensing resolution, nm-size stepping and drifts less than 4nm/hour have been demonstrated.

8851-49, Session PWed

Full-field x-ray nano-imaging at SSRF

Biao Deng, Yuqi Ren, Yudan Wang, Guohao Du, Honglan Xie, Tiqiao Xiao, Shanghai Institute of Applied Physics (China)

A new full field X-ray nano-imaging beamline based at a bending magnet source is included in the SSRF phase-II project. The beamline aims at 3D nano-imaging of nanoscale inner structures. The photon energy range is of 5-14 keV. The design goals of FOV of 20 µm and spatial resolution of 20 nm are proposed at 8 keV with 25 nm FZP outermost zone width. The beamline is composed of, a parabolic cylindrical mirror, a toroidal mirror, double crystal monochromator with 2 sets of crystals for on-line exchange: standard Si (111) crystals and asymmetrically cut crystals. We propose to use asymmetrically cut crystals to regain most of the flux at an acceptable increase in bandwidth. In addition, an X-ray nano-imaging microscope is under developing at SSRF BL13W beamline, in which large field of view will be imaged and the spatial resolution is set to sub 100nm. This microscope is based on beam shaper [1] and zone plate using absorption contrast and zernike phase contrast, with the optimized energy set to 10keV. The detailed design and the progress of the project will be introduced.

References

[1] K. Jefimovs, et al. J. Synchrotron Rad. (2008). 15, 106–108

8851-18, Session 6

Development of synchrotron-radiation-based low-temperature scanning tunneling microscopy (SXSTM) *(Invited Paper)*

Nozomi Shirato, Argonne National Lab. (United States); Heath Kersell, Saw Wai Hla, Ohio Univ. (United States); Marvin Cummings, Curt A. Preissner, Volker Rose, Argonne National Lab. (United States)

High resolution scanning tunneling microscopy (STM) combined with synchrotron X-rays provide an exciting scientific tool to explore surface science. Synchrotron x-ray scanning tunneling microscope (SXSTM), is capable of probing not only topographic and electronic properties but also elemental uniqueness and magnetic states of surfaces from mesoscopic lengths down toward the atomic level. The underlying fundamental mechanism is that the inner-shell electron excitation at a specific level by X-rays can be locally probed by the STM tip, and it allows us to identify chemical and magnetic signals with high spatial resolution. Here we will discuss the ongoing development of a next-generation SXSTM featuring low temperature and high resolution STM with X-ray radiation. The project is based on a prototype instrument that has been developed in our group. Some additional features are incorporated with the new system. For instance, the new compactly designed STM utilizes a flow cryostat to cool the microscope. It helps to meet overall size limitation of an instrument at a synchrotron beamline. The microscope is supported by a three-axis translation and a single axis rotation stage to facilitate the alignment of the tip and sample with respect to the incoming X-ray beam. The challenges and unique opportunities of developing the system will also be discussed.

8851-19, Session 6

Development of an in-vacuum x-ray microscope with cryogenic sample cooling for beamline P11 at PETRA III

Alke F. Meents, Bernd Reime, Nicolas Stuebe, Pontus Fischer, Martin Warmer, Dennis Goeries, Jan Roever, Jan Meyer, DESY (Germany); Ismo J. Vartiainen, Christian David, Paul Scherrer Institut (Switzerland)

Beamline P11 at PETRA III is dedicated to structural investigations of biological samples. In provides two experimental stations, one for macromolecular crystallography and one for X-ray microscopy. The microscope will provide full field Zernike phase contrast and scanning microscopy both in 2D and in tomographic mode. Full field microscopy with a field of view of 50 x 50 µm2 will allow to generate an overview of the sample and to select regions of interest for later inspection of the element distribution by X-ray fluorescence in scanning mode.

Central part of the microscope is an inhouse developed flexure based x,y,z scanner on top of a rotation stage. The scanner is operated in closed loop with piezo motors, has a travel range of 4 mm in horizontal and of 3 mm in vertical direction. With laser interferrometers for closed loop operation a positioning accuracy of better than 5 nm is achieved in all directions. For precise sample rotation an in-vacuum air-bearing has been developed. An open bore in the center of the air-bearing will allow for cryogenic sample cooling by a cold He or N2 gas stream.

Different optical elements such as beam defining pinholes, a condensor, zone plates, OSA, phase rings, etc. can be centered in the beam path by piezomotoer driven x,y flexure elements mounted on a rail system which allows further positiong along the beam path. Different 2D detectors and two fluoresence detectors can be attached to the microscope.

The microscope design and first results will be presented.

8851-20, Session 6

NanoMAX: a hard x-ray nanoprobe beamline at MAX IV

Ulf Johansson, MAX IV Lab. (Sweden); Ulrich Vogt, Royal Institute of Technology (Sweden); Anders Mikkelsen, Lund Univ. (Sweden)

NanoMAX is the name of the first x-ray imaging beamline at the new Swedish synchrotron radiation source MAX IV. It is a hard X-ray undulator beamline for micro- and nanobeams and will enable imaging applications exploring diffraction, scattering and fluorescence methods. A major consideration for the construction of NanoMAX is to utilize MAX IV's exceptional low emittance, high brilliance and coherence properties of the x-ray beam. This should make the NanoMAX beamline a flagship beamline for MAX IV showcasing the full potential of the ring.

NanoMAX aims for a final resolution goal of 10 nm while keeping the option of flexible beam sizes up to about 1 um providing the possibility of matching spot size and divergence to the experimental requirements. The beamline will feature two endstations: One with beamsizes down to 300 nm, extremely well suited for scattering and coherence experiments in very flexible sample environments. A second endstation will make it possible to reach the highest resolution with the options of doing diffraction and fluorescence experiments on very small nanoscale objects.

The technical design of the beamline will be presented, including details on beamline optics layout and simulations, undulator parameters and experimental station equipment. The design of the dedicated experimental station building and other infrastructure will also be described.

The NanoMAX beamline project got funded late 2011 and the beamline is planned to open to users late 2016.

8851-21, Session 6

A dedicated hard x-ray diffraction nanoprobe beamline for materials studies at APS

Zhonghou Cai, Wenjun Liu, Jonathan Z. Tischler, Ruqing Xu, Deming Shu, Oliver Schmidt, Argonne National Lab. (United States)

Aiming at studies of the micro/nanostructures of a broad range materials and electronic devices, Advance Photon Source (APS) is developing a diffraction nanoprobe beamline for the needs arising from a multidiscipline research community. The planed facility integrates the K-B mirror based polychromatic Laue diffraction and the Fresnel zone-plate based monochromatic diffraction techniques that currently support 3D/2D microdiffraction programs at the 34-ID-E and 2-ID-D of the APS, respectively, and both are designed to have a 50-nm or better special resolution. As a part of the APS Upgrade Project, the nanoprobe beamline has been preliminarily designed and will be constructed at the sector 34-ID. The nanoprobe facility uses an APS-3.0-cm period undulator, a liquid-nitrogen cooled mirror as its first optics, and a water cooled small gap silicon double-crystal monochromator of an energy range of 5-30 keV. The ultra-precision focusing mirror with low figure error and surface roughness and a set of zone plates have been designed to optimize for focusing efficiency and the working distance based on the attainable beamline length and the beam coherence. To ensure the nanoprobe performance, high stiffness and high precision flexure stage systems have been designed for optics mounting and sample scanning, and high precision temperature control of the experimental station will be implemented to reduce thermal instability. Designed nanoprobe beamline has a good management on thermal power loading on optical components and allows high degree of the preservation of beam brilliance for high focal flux and coherence. Integrated with variety of X-ray techniques, planed facility provides nano-XRD capability with the maximum reciprocal space accessibility and allows micro/nano-spectroscopy studies with K-edge electron binding energies of most elements down to Vanadium in the periodic table. We will discuss the preliminary design of the diffraction nanoprobe beamline and its technical relevance to a broad range of scientific applications.

8851-22, Session 6

Data analysis for x-ray fluorescence microscopy: unique challenges and opportunities

Stefan Vogt, Siwei Wang, Jesse Ward, Stefan Wild, Argonne National Lab. (United States); Martin D. de Jonge, Australian Synchrotron (Australia); Barry Lai, Sven Leyffer, Chris J. Jacobsen, Argonne National Lab. (United States)

X-ray fluorescence microscopy (XFM) is a powerful technique to map and quantify trace element distributions in biological specimens. It is perfectly placed to map nanoparticles and nanovectors within cells, at high spatial resolution. Advances in instrumentation, such as faster detectors, better optics, and improved data acquisition strategies are fundamentally changing the way experiments can be carried out, giving us the ability to more completely interrogate samples, at higher spatial resolution, higher throughput and better sensitivity. We have also developed software tools such as 'MAPS', that enable routine data processing of XFM datasets, including per-pixel fitting of full spectra and quantification of acquired elemental maps, principle component as well as cluster analysis.

Yet one thing is still missing: the next generation of data analysis and visualization tools for multidimensional microscopy that can interpret data, identify and classify objects within datasets, visualize trends across datasets and instruments, and ultimately enable researchers to reason with abstraction of data instead of just with images. We will report on the software tools for X-ray fluorescence microscopy at the APS, including on the latest developments. For example, we will demonstrate automated analysis by locating cells positions in a complex XFM dataset via image segmentation, determining exact cell regions via models of elemental content and cell shape, accounting for overlapping structures, and successfully distinguishing different cell types.

We will also identify unique challenges and opportunities brought about by instrumentation advances, and discuss steps we have taken to exploit these opportunities through advances in data analysis.

8851-23, Session 7

CSI using XFM: chemical state imaging using fast x-ray fluorescence microscopy

David J. Paterson, Martin D. de Jonge, Daryl L. Howard, Kathryn Spiers, Australian Synchrotron (Australia); Chris G. Ryan, Robin Kirkham, Commonwealth Scientific and Industrial Research Organisation (Australia)

X-ray fluorescence microscopy (XFM) can be used for elemental and chemical microanalysis across length scales from the millimeter to the nanometer. Advances in X-ray fluorescence detection schemes such as the Maia detector now enable high definition images at mega-pixel per hour rates. Fast XFM also enables 3D scans such as fluorescence tomography to be acquired in realistic times. Chemical speciation (valence) imaging (CSI) is a 3D technique where the third dimension becomes incident energy producing an X-ray Absorption Near Edge Structure spectra at each pixel. Recent examples of CSI at the Australian XFM beamline will be presented.

8851-24, Session 7

Simultaneous fast scanning XRF, dark field, phase-, and absorption contrast tomography

Kadda Medjoubi, Nicolas Leclercq, Florent Langlois, Pascal Mercère, Andrea Somogyi, Synchrotron SOLEIL (France)

Hard X-ray nanoprobe imaging provides a unique tool for probing specimens with high sensitivity and large penetration depth. Moreover, the combination of complementary techniques such as X-ray fluorescence, absorption, phase contrast and dark field imaging gives complete quantitative information about the sample structure, composition and chemistry.

The multi-technique fast “Flyscan” data acquisition scheme developed at Synchrotron SOLEIL [1] makes scanning tomography techniques feasible in a time-frame well-adapted to typical user experiments. Here we present the recent results of simultaneous fast scanning multi-technique tomography performed at Soleil. This fast scanning scheme will be implemented at the Nanoscopium beamline for large field of view 2D and 3D multimodal scanning imaging.

[1] Medjoubi et al., J. Synchrotron Rad. (2013). 20, 293-299

8851-25, Session 7

The Maia detector array and x-ray fluorescence imaging system

Chris G. Ryan, Commonwealth Scientific and Industrial Research Organisation (Australia); David P. Siddons, Brookhaven National Lab. (United States); Robin Kirkham, Commonwealth Scientific and Industrial Research Organisation (Australia); Zhi Yong Li, Brookhaven National Lab. (United States); Martin D. de Jonge, David J. Paterson, Australian Synchrotron (Australia); James S. Cleverley, Commonwealth Scientific and Industrial Research Organisation (Australia); Anthony J. Kuczewski, Brookhaven National Lab. (United States); Paul A. Dunn, Murray Jensen, Commonwealth Scientific and Industrial Research Organisation (Australia); Gianluigi De Geronimo, Brookhaven National Lab. (United States); Daryl L. Howard, Australian Synchrotron (Australia); Gareth F. Moorhead, Commonwealth Scientific and Industrial Research Organisation (Australia); Simon A. James, Kathryn Spiers, Australian Synchrotron (Australia); Gerald Falkenberg, Gerd Wellenreuther, Ulrike Boesenberg, DESY (Germany); Stacey Borg, Commonwealth Scientific and Industrial Research Organisation (Australia)

X-ray fluorescence images collected using the Maia detector array and integrated real-time processor [1] on the X-ray Fluorescence Microscopy (XFM) beamline at the Australian Synchrotron [2] capture fine detail in element images up to ~100M pixels. Maia combines a large solid-angle annular energy-dispersive 384 detector array, stage encoder and flux counter inputs and dedicated FPGA-based real-time event processor enabling high definition imaging and enhanced sensitivity to capture the complex hierarchical detail in natural samples and detect rare trace structures and place them in a detailed spatial context. Methods have been developed for the real-time display of deconvoluted SXRF element images and for the acquisition of 3D data-sets for fluorescence tomography and chemical state (XANES) imaging.

This paper describes recent refinements in Maia hardware performance, methods for per pixel correction for pixel dwell and beam flux variation aimed at high quality images, methods for efficient processing of XANES image stacks, quantitative on-line images and off-line parallel processing methods for enhanced throughput, illustrated using complex geological, environmental and biological sample high definition data-sets acquired at the XFM beamline and recent data collected on the Hard X-ray Micro/Nanoprobe beamline P06 HASYLAB at DESY [3].

References:

[1] R. Kirkham et al., AIP Conference Proceedings 1234, 240-243 (2010).

[2] D. Paterson et al., AIP Conference Proceedings 1365, 219 (2011).

[3] Schroer et al., Nucl. Instr. Meth. A 616, 93 (2010).

8851-26, Session 7

Ultrafast pulse processing electronics for high-flux florescence microscopy

Paul A. Scoullar, Southern Innovation (Australia); Peter M. Grudberg, XIA LLC (United States)

Many applications of florescence microscopy are severely limited by detector dead time. Historically, analogue pulse shaping was used to analyze detector output, however, digital pulse processing has been recognized as having advantages including: robustness against noise; and extended operational count rate range. We present a novel approach to detector pulse processing utilizing model based signal processing techniques and accurate parameter estimation. Using these techniques pile-up can be decomposed into the individual component events in real-time. By decoding pulse pile-up on the fly, little data is rejected resulting in a dramatic improvement in throughput without the traditional loss of energy resolution.

8851-27, Session 8

Hard x-ray scanning microscopy with coherent radiation: beyond the resolution of conventional x-ray microscopes *(Invited Paper)*

Christian G. Schroer, Technische Univ. Dresden (Germany); Andreas Schropp, Technische Univ. Dresden (Germany) and SLAC National Accelerator Lab. (United States); Robert Hoppe, Jens Patommel, Dirk Samberg, Frank Seiboth, Sandra Stephan, Technische Univ. Dresden (Germany); Gerd Wellenreuther, Gerald Falkenberg, DESY (Germany)

Based on nanofocusing refractive x-ray lenses we have built a hard x-ray scanning microscope at the synchrotron radiation source PETRA III at DESY in Hamburg. This instrument can make use of conventional x-ray analytical techniques, such as x-ray fluorescence, absorption, and diffraction in order to image an object with elemental, chemical, or nano structural contrast, respectively. In addition, it is optimized for coherent x-ray diffraction imaging techniques. We demonstrate x-ray scanning coherent diffraction microscopy (ptychography) with 10 nm

spatial resolution, clearly exceeding the resolution limits of conventional hard x-ray microscopy. The spatial resolution in a ptychogram is shown to depend on the shape (structure factor) of a feature and can vary for different features in the object. In addition, the resolution and contrast is shown to increase with increasing coherent fluence. For an optimal ptychographic x-ray microscope this implies a source with highest possible brilliance and ultimately an x-ray optic with a large numerical aperture to generate the optimal probe beam. The current limitations and future opportunities are discussed.

8851-28, Session 8

Coherent diffraction imaging of a complex sample with partially coherent source

Bo Chen, Brian Abbey, Mark Junker, La Trobe Univ. (Australia); Harry M. Quiney, The Univ. of Melbourne (Australia); Alberto Cereser, Mac Luu, Grant A. van Riessen, Keith A. Nugent, La Trobe Univ. (Australia)

Coherent Diffraction Imaging (CDI) is an important imaging method to look at the sample with the resolution of tens to several nanometers. With the development of modern X-ray source such as third-generation synchrotron and X-ray Free Electron Laser(XFEL), it is now possible to observe the inside structure or even molecular interaction in the sample without the need of section like traditional scanning electron microscopy (SEM). This is very important for a situ imaging. Because of the potential of its application in sciences, CDI has been used widely in material and biological sample since its first demonstration in experiment.

Although CDI has shown particular promise in applications involving X-ray free electron lasers and third generation synchrotron, the limited coherent output of these sources is the barrier to its application in practice. To get a successful data in traditional CDI experiment, the source is usually monochromated and spatially filtered so that the sample is illuminated with a highly coherent source. By doing this way, the most concerned issue is the loss of the flux. Due to the decrease of flux, the exposure time is usually much longer than 1s for every shot, thus the requirement to the stability of the experimental system is high. And it will prevent scientist from investigating the sample in real time. The problem can be solved by using a polychromatic source in the experiment. This was first realized in high-harmonic generation (HHG) imaging by using all harmonics in the experiment. Recently, a new CDI method with broadband beam ("polyCDI") has been demonstrated. In polyCDI, the source is considered as the combination of many monochromatic coherent modes with different frequencies. This requires that the spatial coherence of the source should still be high. For a real source, however, the coherent length is not always necessarily longer than the sample. So most likely, the sample is illuminated with a partially coherent source, which will blur the diffraction pattern thus decrease the resolution of the reconstruction. When the blur is serious, it is proved that the traditional CDI algorithm will fail and a partial CDI (PCDI) algorithm is needed for a good reconstruction .

In this presentation, we demonstrated that it is possible to include both spatially partial and temporally partial coherence in CDI reconstruction (pink PCDI) for a complex sample. We also analyzed the limit of the coherence length and bandwidth to this method.

8851-29, Session 8

Simultaneous x-ray fluorescence and ptychographic microscopy

David J. Vine, Argonne National Lab. (United States)

Combining X-ray fluorescence microscopy with ptychography is powerful because the contrast mechanisms of the two techniques are complementary. The X-ray fluorescence signal is sensitive to the elemental composition whereas ptychography, which images the complex transmission function, is sensitive to the electron density. Progress toward implementing ptychography at scanning X-ray fluorescence beamlines at the APS will be described as well as recent results.

8851-30, Session 8

Development of coherent x-ray zoom condenser lens for diffractive and scanning imaging

Takashi Kimura, Hokkaido Univ. (Japan); Satoshi Matsuyama, Hiroki Nakamori, Takumi Goto, Yasuhisa Sano, Osaka Univ. (Japan); Tetsuya Ishikawa, RIKEN (Japan); Yoshinori Nishino, Hokkaido Univ. (Japan); Kazuto Yamauchi, Osaka Univ. (Japan)

In this presentation, we propose a new optical system which adds a zooming function to x-ray diffraction microscope by controlling the x-ray beam size of coherent illumination. We propose two-stage deformable Kirkpatrick-Baez (KB) mirror optics to keep diffraction-limited focusing condition, ideal for x-ray diffraction microscope, with varying beam sizes. By extending our previous studies [1] to use deformable mirrors to compensate the figure error of condenser mirrors, we control the numerical aperture of condenser mirrors.

The proposed two-stage deformable KB mirror optics is designed to keep the focal length. It realizes diffraction-limited focused beam with variable sizes at a fixed sample position, as we confirmed by wave-optical simulation. This feature considerably simplifies microscope instruments and one can more easily zoom up regions of interest in sample in x-ray diffraction microscopy measurement.

We also propose a new image-reconstruction algorithm for extended objects from a single diffraction pattern by using the two-stage deformable KB mirror optics. The optics has two focal points, and one can create a spatially confined illumination by adequately putting a spatial filter at the first focal point. With this illumination, an extended sample can be regarded as isolated object, and sample images can be reconstructed without ptychographic procedures.

[1] H. Mimura et at., Nat. Phys. 6, 122(2010)

8851-31, Session 9

Optimized cavity-enhanced x-ray sources for x-ray microscopy *(Invited Paper)*

John M. Madey, Eric B. Szarmes, Michael Hadmack, Jeremy Kowalczyk, Univ. of Hawai'i (United States)

Assuming an electron beam emittance small in comparison to the wavelength of the colliding IR or optical photons, it can be shown that the total average power radiated by an inverse Compton light source with optimally focussed colliding electron and optical beams scales simply as the product of the instantaneous peak optical power and average electron current of the colliding optical and electron bunches. The principal challenge in designing such a source is therefore to find the combination of optical and accelerator technologies that can maximize this product at the desired final state photon energy subject to the constraints imposed by the limits on the peak power of the colliding optical pulses, the limits set by optical damage and thermal expansion of the optics for the system, and the available ebeam accelerator technology. A substantial enhancement in the radiated power at x-ray wavelengths can be attained in principal through the use of a high finesse optical storage cavity to integrate the output of a lower power phase. coherent pump laser. But it is generally impossible to achieve the required performance using a simple two-mirror resonator. We will describe a project at the University of Hawai'i to demonstrate the optical and accelerator technology needed to operate such an optimized high performance X-ray source at photon energies from 10-20 keV.

8851-32, Session 9

Establishing nanoscale laboratory hard x-ray microscopy in the Central Microscopy Laboratory

Michael Feser, Xradia, Inc. (United States)

3-D X-ray Microscopes with sub-50nm spatial resolution are establishing themselves in the central microscopy laboratory alongside optical and particle based microscopy techniques. Advances in x-ray optics, instrumentation, automation and algorithms have made these type of microscopes attractive to complement established microscopy tool sets. The ability to perform repeated non-destructive 3-D scans of larger samples and hierarchically focusing in on features of interest make x-ray microscopes an indispensable tool for 4-D (time, evolution) studies before preparing the sample for a destructive (FIB/e-beam) microscopy technique. Current performance, application and correlative workflow examples are presented.

8851-33, Session 9

Tabletop coherent diffractive imaging of extended objects in transmission and reflection geometry

Matthew D. Seaberg, Bosheng Zhang, Daniel E. Adams, Dennis F. Gardner Jr., Henry C. Kapteyn, Margaret M. Murnane, Univ. of Colorado at Boulder (United States)

Recent breakthroughs in high harmonic generation have extended the reach of bright tabletop coherent light sources from a previous limit of ≈100eV, in the extreme ultraviolet (EUV), all the way beyond 1keV in the soft X-ray region. Due to its intrinsically short pulse duration and spatial coherence, this light source can be used to probe physical processes at the femtosecond timescale, with nanometer-scale spatial resolution using a technique called coherent diffractive imaging (CDI).

CDI is an aberration-free technique that replaces image-forming optics with a computer phase retrieval algorithm, which recovers the phase of a measured diffraction amplitude. This technique typically requires the sample of interest to be isolated; however, it is possible to relax this constraint by imposing this requirement on the illumination. One such modification to the technique has been termed keyhole CDI, in which a hard edge is placed on the beam on its way to the focus.

Here we extend previous tabletop results, in which we demonstrated the ability to image a test object with 22nm resolution with 13nm light, to imaging of more complex samples using the keyhole technique adapted to our source. We have recently demonstrated the ability to image extended objects in a transmission geometry with ≈100nm resolution. Finally, we have taken preliminary CDI measurements of extended nanosystems in reflection geometry. We expect that this capability will soon allow us to image dynamic processes in nanosystems at the femtosecond and nanometer scale.

Conference 8852: Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XV

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8852-1, Session 1

Physics of scintillator light yield nonproportionality *(Invited Paper)*

Stephen A. Payne, Nerine J. Cherepy, Steven L. Hunter, Lawrence Ahle, Lawrence Livermore National Lab. (United States); Gregory A. Bizarri, William W. Moses, Lawrence Berkeley National Lab. (United States)

This presentation is on our work in elucidating the physics of light yield nonproportionality in scintillators. We have recently recorded the temperature dependence of the nonproportionality curves for doped CsI and NaI, and for several oxides; we have interpreted the results in terms of the impact on the migration of excitons. We have also studied a large number of Cerium-doped garnet-structure materials, and observed the impact of both composition and defects on the nonproportionality. We will summarize our experimental and modeled results on a large variety of different halide and oxide hosts, and finally describe the (expected) differences in the energy resolution and light yields characteristic of gammas versus electrons due to Compton scattering and the distribution of electrons created by photoelectric absorption.

Acknowledgements: This work was performed under the auspices of the U.S. DOE by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and has been supported by the US Department of Energy, Office of Nonproliferation Research and Development.

8852-2, Session 1

Time-encoded imaging of energetic radiation

Erik Brubaker, James Brennan, Peter Marleau, Kyle McMillan, Aaron Nowack, Nathalie Renard-Le Galloudec, Patricia Schuster, Sandia National Labs. (United States)

Time-encoded imaging (TEI) is a new approach to directional detection of energetic radiation that produces images by inducing a time-dependent modulation of detected particles. TEI-based detectors use single-scatter events and have a low channel count, reducing complexity and cost while maintaining high efficiency with respect to other radiation imaging techniques such as double-scatter or coded aperture imaging. The scalability of TEI systems makes them a very promising detector class for weak source detection. Extension of the technique to high-resolution imaging is also under study.

Experimentally, we have focused on fast neutron detection and imaging using TEI. Briefly, in time-encoded neutron imaging, a time modulation of a detected neutron signal is induced—for example, a moving mask that attenuates neutrons with a time structure that depends on the source position. Time-encoded imaging is in many ways analogous to coded aperture imaging; the spatial modulation of a particle flux induced by a fixed mask on a position-sensitive image plane is replaced by the time modulation of a particle flux induced by a moving mask on one or a few time-sensitive detectors.

With a prototype time-encoding detector, we demonstrated detection of a neutron source at 60 m with neutron output equivalent to an IAEA significant quantity of WGPu. We have since designed and built a full-scale detector based on the time-encoding concept. We will present results from characterization of very large liquid scintillator cells, including pulse shape discrimination, as well as from studies of the detector system performance in weak source detection scenarios.

8852-3, Session 1

Theoretical investigation of potential low-band gap scintillators

David J. Singh, Mao-Hua Du, Oak Ridge National Lab. (United States)

Most well developed scintillators for spectroscopic gamma detection have emission energies compatible with photomultiplier tubes. However, alternate light detection components, such as silicon photodiodes, allow for the use of lower emission energy scintillators. This is enabling for lower band gap scintillators which may potentially have higher light yield, and ultimate energy resolutions better than conventional materials. Here we present results from theoretical studies of lower band gap heavy halide materials and their activation to form new scintillator materials.

8852-4, Session 1

First-principles study of electronic structure, defects, and activators in LiCaAlF6

Mao-Hua Du, David J. Singh, Oak Ridge National Lab. (United States)

LiCaAlF6 (LiCAF) is a promising inorganic neutron scintillator material. Here, we report the electronic structure as well as properties of the small hole polaron, F center, and activators (e.g., Ce) in LiCAF based on first-principles calculations. These results are discussed in the context of carrier transport and trapping in LiCAF. We also discuss the approach to reduce reabsorption of Ce emission by the F centers, thereby suppressing afterglow in LiCAF:Ce after exposure to X- or gamma-ray.

8852-5, Session 2

Performance of 3D position-sensitive CdZnTe pixelated detectors *(Invited Paper)*

Aleksey E. Bolotnikov, Giuseppe S. Camarda, Yonggang Cui, Brookhaven National Lab. (United States); Václav Dedic, Charles Univ. in Prague (Czech Republic); Gianluigi De Geronimo, Jack Fried, Matthew Marshall, Brookhaven National Lab. (United States); Kisung Lee, Korea Univ. (Korea, Republic of); Utpal N. Roy, Matthew Petryk, Emerson Vernon, Ge Yang, Ralph B. James, Brookhaven National Lab. (United States)

We will describe the effects of the pixel geometry, readout electronics, and crystal defects on the performance of CdZnTe (CZT) pixelated detectors. The presented results provide insight into important details about the performance of CZT pixelated detectors and the relationship to pixel dimensions and crystal quality.

8852-6, Session 2

Drift time dependent CPG pulse height correction

Christian Disch, Alex Fauler, Andreas Zwerger, Freiburger Materialforschungszentrum (Germany); Markus Dambacher, X-RAY IMAGING EUROPE GmbH (Germany); Michael Fiederle, Freiburger Materialforschungszentrum (Germany)

High detector efficiency, especially at high photon energies, requires thick

detectors with large absorption. However, thick detectors with planar contacts usually show a strong correlation between pulse shape/height and interaction depth, causing low energy tailing and degraded energy resolution. Several different approaches circumvent this problem:

A) Low temperature detectors, e.g. LN2 cooled Germanium, with increased charge carrier lifetime and minimized charge carrier loss;

B) Coplanar Grid (CPG) detectors based on (Cd,Zn)Te, using a special anode configuration and subtraction of anode signals in order to remove nearly all hole contribution from the resulting signal;

C) Pixelated detectors, which effectively count the number of electrons reaching each anode pixel.

While low temperature detectors require constant and expensive cooling, and pixelated detectors demand complex read-out electronics, CPG detectors offer good compromise if one is only interested in energy information coupled with cheap room-temperature detector material and simple read-out electronics.

It has been shown, that multi-hit events degrade the energy resolution of detectors. Identifying and suppressing or correcting these events can increase detector performance. We will introduce a new method that uses hole drift times to correct standard CPG anode signals for interaction-depth dependent charge loss in case of multi- and single-hit events. 7 mm thick material is used with a CPG anode structure and modified cathode contact, enabling the precise measurement of drift times and subsequent correction of electron signals. Energy spectra with and without correction are presented, as well as a discussion of theoretical and actual improvements.

8852-7, Session 2

Etch-pit analysis of Cd(Zn,Mn)Te crystals grown by different methods

Anwar Hossain, Aleksey E. Bolotnikov, Giuseppe S. Camarda, Yonggang Cui, Genda Gu, Utpal N. Roy, Ge Yang, Ralph B. James, Brookhaven National Lab. (United States)

We evaluated the etch-pit distribution on the surface of cadmium zinc telluride (CZT) and cadmium manganese telluride (CMT) crystals grown by high-pressure Bridgman (HPB), travelling heater method (THM) and floating zone (FZ) method. Etch pits have been revealed on the crystals' surfaces by using different chemical etchants (e.g., Nakagawa, EAg with different silver concentrations, and Saucedo solutions). We have analyzed the pits' geometry, sizes, and densities to correlate them with the nature of the crystal's defects. We evaluated the areal densities and distributions of the etch pits associated with dislocations and other crystallographic defects using IR transmission microscopy and a scanning electron microscopy (SEM) combined with energy-dispersive x-ray spectroscopy (EDS). Results of these studies will be presented.

8852-8, Session 2

Atomic and electronic structure of dislocations in CdTe

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Cadmium telluride (CdTe) and related alloys such as CdZnTe are leading candidates for high energy-resolution, room-temperature semiconductor gamma and X-ray radiation detectors. Present limitations in performance are mainly due to defects found in large melt-grown crystals. Such defects range in scale from point defects to dislocations to twins and grain boundaries. These defects degrade detector performance primarily by reducing carrier lifetimes in the material through the introduction of deep electron traps. Understanding the electronic structure of the defects therefore is critical to optimizing material performance.

This work focuses on a theoretical determination of the impact of dislocations on the electronic properties of CdTe. First-principles calculations based on density functional theory are used to study the atomic and electronic structure of prototypical screw and edge dislocation cores in CdTe. The accuracy of the description of long-range strain around the dislocation core is studied by carefully examining finite-size and edge termination effects in the atomic models. From the atomic-scale structural descriptions of the dislocation cores, we obtain their associated spectra of gap electronic states using large-scale electronic structure calculations, allowing direct assessment of the impact on device electrical performance.

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8852-9, Session 3

Heavy metal ternary halides for room-temperature x-ray and gamma-ray detection

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Efficient x-ray and gamma-ray radiation detectors have attracted interest for nondestructive testing, medical imaging, and security applications. For radiation detection at room temperature, semiconductor compounds with wide bandgaps, high average atomic numbers, high resistivity, and high mass densities are sought after. Compound semiconductors such as CdZnTe, CdTe, HgI2, PbI2, and TlBr are finding applications as detector development continues. We report our recent developments on synthesis, crystal growth, and characterization of the ternary heavy metal halides CsPbBr3 and CsPbCl3 for room temperature radiation detectors. The compounds are grown by a modified Bridgman method. The size of cut crystals is 2.1mm in thickness, 7.0mm in diameter. At room temperature, CsPbBr3 has an orthorhombic Pnma structure, and CsPbCl3 has the I4/mmm tetragonal structure. CsPbBr3 and CsPbCl3 have melting points at 567, and 610 degree Celsius, respectively. The absorption coefficients and bandgap energies were determined from UV-Vis-near IR transmission and reflection spectra. The energy bandgaps of CsPbBr3 and CsPbCl3 are 2.24 eV and 2.86 eV, respectively. The mobility-lifetime products for electron and hole carriers were determined from photoconductivity measurements. The measured mobility-lifetime products of CsPbBr3 for electron and hole carriers are 1.7x10^(-3), 1.3x10^(-3) cm^2/V, respectively. A key property that affects detector performance is the minority carrier lifetime. The lifetime of minority carrier (electron) is 2.54 microseconds as measured by photoconductivity decay. Photoluminescence spectroscopy was used to determine radiative defects present in these materials. Band edge emission in the 2.29 - 2.38 eV spectral region was observed at 30-80 K. We measured the x-ray spectral response of CsPbBr3 detector to Ag x-ray radiation at 295 K. It has a well-resolved spectral response to the 22.4 keV Ka radiation peak. Its efficiency is comparable to that of a commercial CdZnTe detector.

8852-10, Session 3

Basic studies on x-ray fluorescence analysis for active x-ray spectrometer on SELENE-2

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The active X-ray spectrometer (AXS) is now being developed as a payload candidate for SELENE-2, a next Japanese lunar exploration mission. The AXS is an in-situ X-ray fluorescence analyzer, which is to

determine the concentrations of major and sub-major elements and to characterize the geochemistry of lunar rocks and regolith around the landing site. The AXS will provide better understandings of the present lunar surface and its formation process. The AXS consists of a silicon drift detector (SDD) and multiple pyroelectric X-ray generators, and is to be installed on the top of rover arm together with a rock abrasion tool (RAT). The surface of lunar rock samples is needed to be grinded using the RAT because the surface of lunar rocks is weathered by the space weathering effect due to meteoroids and energetic particles. In this study, we have been investigating the X-ray fluorescence analysis (XRF) of rocks for evaluating the requirements for AXS on the Moon. The effect of surface roughness of rocks and the angle between incident and outgoing X-rays in XRF were studied from experiments and simulations. The XRF experiments were carried out using a SDD and an X-ray tube in a vacuum chamber. Geochemical reference samples with different surface roughness were used for the experiments. The XRF simulations were also carried out using the PENELOPE code. Fluorescent X-ray counts for some chemical elements were found to depend on the roughness and angle. The results of XRF for the AXS on SELENE-2 will be presented and discussed.

8852-11, Session 3

ZnO thin-film transistors for radiation environment applications

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Radiation tolerance is of interest for space use and harsh environment applications such as nuclear reactors, and high-energy particle accelerators. While properly designed Si MOSFETS are usefully radiation resistant, most thin-film transistors (TFTs), including polysilicon and a-Si:H, are severely degraded by relatively low irradiation dose (typically <1 MRad). ZnO is a versatile semiconductor with a wide bandgap (Eg = 3.37 eV). The bonding in ZnO is strongly ionic and states near the conduction band minimum arise almost completely from cation (zinc) s-orbitals. This is in strong contrast to covalent or nearly covalent semiconductors like Si or GaAs where sp-bonding is sensitive to both bond angle and bond length disorder that easily generates localized states (traps). In ZnO, the nearly spherical and relatively large orbitals that form the conduction band result in electronic transport that is largely unaffected by bond angle or bond length disorder and disorder does not easily result in localized states.

We have done 60Co gamma ray irradiation testing of ZnO TFTs with and without electrical bias. The ZnO semiconductor and Al2O3 dielectric films used in these TFTs were deposited by weak oxidant plasma enhanced atomic layer deposition (PEALD). Devices irradiated without bias have only small changes in electrical properties for dose up to 100 Mrad; TFTs irradiated while biased in the linear or saturation region have somewhat larger changes. Irradiation induced changes for both biased and unbiased TFTs are nearly completely removed by a 60 s anneal at 200 °C.

8852-12, Session 3

Fabrication of high-resolution n-type 4H-SiC epitaxial layer alpha particle detectors and electronic noise analysis

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In the present work high-resolution alpha particle detectors have been fabricated on high quality 20 micron thick n-type 4H-SiC epitaxial layers. A micropipe density lower than 1 cm^-2 was evaluated in the epilayers using Nomarski optical microscopy and scanning electron microscopy. Schottky barrier detectors have been fabricated by depositing 10 nm thick nickel contacts on the Si face of the epilayers. The detectors were characterized using current-voltage (I-V), capacitance-voltage (C-V) and alpha spectroscopic measurements. I-V measurements revealed a typical barrier height of ~1.6 eV, diode ideality factor of 1.09, and leakage current of the order of 14 pA at an operating bias of 110 V. C-V measurements revealed low effective doping concentrations of 2.4 x 10^14 cm^-3 in the epilayers. Pulse-height spectroscopy exhibited energy resolution as high as 0.37 % for 5.48 MeV alpha particles with a detector active area of 11 mm^2. A diffusion length of ~13.2 micron for holes has been determined in these detectors following a calculation based on a drift-diffusion model. Detailed electronic noise analysis in terms of equivalent noise charge (ENC) was carried out to study the effect of various noise components that contribute to the total electronic noise in the detection system. Shaping time and bias dependence of ENC has been studied in details. The noise analysis revealed that the white series noise due to the detector capacitance has substantial effect on the detector's overall performance.

8852-13, Session 3

Photoemission spectroscopic analysis of chemically modified TlBr surfaces for improved radiation detectors

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Device-grade TlBr was subjected to various chemical treatments used in room temperature radiation detector fabrication to determine the resulting surface composition and electronic structure. Samples of as polished TlBr were treated separately with 10%HCl, 96%SOCl2, 2%Br:MeOH and 10%HF solutions. High-resolution photoemission measurements on the valence band electronic structure and Tl 4f, Br 3d, Cl 2p and S 2p core lines were used to evaluate surface chemistry. Results suggest anion substitution at the surface with subsequent shallow heterojunction formation. Surface chemistry and valence band electronic structure were further correlated with the goal of optimizing the long-term stability and radiation response.

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8852-14, Session 4

pnCCDs for imaging and spectroscopy of x-rays up to 100 keV *(Invited Paper)*

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X-ray CCDs have been used in the past for imaging and spectroscopy of X-rays in the energy band from 100 eV up to 10 keV in X-ray astronomy, material and synchrotron science. An extension towards higher energies was realized in several applications by coupling the CCDs to scintillators. Only a few attempts were made to simultaneously exploit the good spectroscopic properties of the direct detection of X-rays in the silicon

bulk and the conversion of the X-rays into visible light in a scintillator coupled to the same CCD. We report on a concept of a pnCCD coupled to an inorganic scintillator (CsI (Tl)) for use in synchrotron experiments with hard X-rays up to 100 keV like PETRA3, BESSY 2 or ESRF. In case the X-rays are interacting in the 500 μm volume of the fully sensitive pnCCD bulk, the created electron-hole pairs deliver position and amplitude with high resolution. In case the interaction takes place in the scintillator the generated light spreads over many pixels. At that point the quantum detection efficiency is close to one, position can be precisely reconstructed but the energy resolution is poor. As the scintillation light levels in the pixel are low, the system must be operated with very low noise. Signals from X-rays directly converted in the silicon and the light from the scintillator may overlap, but can be separated offline. The relevant parameters of such a system were studied and the perspectives for the use in dedicated diffraction experiments at synchrotrons were derived.

8852-15, Session 4

Compact low-noise preamplifier for noise spectroscopy with biased photodiodes in cargo inspection systems

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Noise Spectroscopy, a.k.a. Z-determination by Statistical Count-rate ANalysis (Z-SCAN), is a statistical technique to determine a quantity called the “noise figure” from digitized waveforms of pulses of transmitted x-rays in cargo inspection systems. Depending only on quantities related to the x-ray energies, it measures a characteristic of the transmitted x-ray spectrum, which depends on the atomic number, Z, of the material penetrated. The noise figure can thus be used for material separation [1][2]. In an 80-detector prototype, scintillators are used with large-area photodiodes biased at 80V and digitized using 50-MSPS 12-bit ADC boards. We present an ultra-compact low-noise preamplifier design, with one high-gain and one low-gain channel per detector for improved dynamic range. To achieve adequate detection sensitivity and spatial resolution, each dual-gain preamplifier channel must fit within a 12.7 mm wide circuit board footprint and maintain adequate noise immunity to conducted and radiated interference from adjacent channels. The novel design included iterative SPICE analysis of transient response, dynamic range, frequency response, and noise analysis to optimize the selection and configuration of amplifiers and filter response. We discuss low-noise active and passive components and low-noise techniques for circuit board layout that are essential to achieving the design goals, and how the completed circuit board performed in comparison to the predicted responses.

[1] Langeveld et al., Nucl. Inst. Meth. A 652 (2011), 79.

[2] Langeveld et al., SORMA 2012, to be published in IEEE Trans. Nucl. Sc.

8852-16, Session 4

Exploitation of geometric occlusion and covariance spectroscopy in a gamma sensor array

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The National Security Technologies, LLC, Remote Sensing Laboratory has recently used an array of six small-footprint (1-inch diameter by 3-inch long) cylindrical crystals of thallium-doped sodium iodide scintillators to obtain angular information from discrete gamma ray emitting point sources. Obtaining angular information in a near-field measurement for a field-deployed gamma sensor is a requirement for radiological emergency work. Three of the sensors sit at the vertices of a 2-inch isosceles triangle, while the other three sit on the circumference of a 3-inch-radius circle centered in this triangle. This configuration exploits occlusion of sensors, correlation from Compton scattering within a detector array, and covariance spectroscopy, a spectral coincidence technique.

Careful placement and orientation of individual detectors with reference to other detectors in an array can provide improved angular resolution for determining the source position by occlusion mechanism. By evaluating the values of, and the uncertainties in, the photopeak areas, efficiencies, branching ratio, peak area correction factors, and the correlations between these quantities, one can determine the precise activity of a particular radioisotope from a mixture of radioisotopes that have overlapping photopeaks that are ordinarily hard to deconvolve. The spectral coincidence technique, often known as covariance spectroscopy, examines the correlations and fluctuations in data that contain valuable information about radiation sources, transport media, and detection systems. Covariance spectroscopy enhances radionuclide identification techniques, provides directional information, and makes weaker gamma-ray emission—normally undetectable by common spectroscopic analysis—detectable. A series of experimental results using the concept of covariance spectroscopy are presented.

8852-19, Session 4

Characterization of the Yale PIXeY two-phase xenon detector

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PIXeY (Particle Identification in Xenon at Yale) is a two-phase (liquid/gas) xenon prototype detector with 3-kg active mass. The two-phase xenon technology has many applications that include gamma-ray imaging, neutrinoless double beta decay searches, and dark matter searches. PIXeY was built to optimize energy resolution and gamma/neutron discrimination, with a number of technological improvements over previous work. Parallel-wire grids, which control the drift and proportional-scintillation fields, are optimized both for light collection efficiency and field uniformity. High quantum efficiency Hamamatsu R8778 PMTs, high-reflectivity Teflon walls, and charge-light anti-correlation techniques are also incorporated. PIXeY will serve as a platform for future improvements, including multiple optical volumes and single wire readout for R&D on gamma-ray imaging and track-imaging studies. The latest progress on the detector will be presented.

8852-20, Session 5

Experimental and computational results on exciton/free-carrier ratio, hot/thermalized carrier diffusion, and linear/nonlinear rate constants for scintillator proportionality *(Invited Paper)*

Richard T. Williams, Joel Q. Grim, Qi Li, Kamil B. Ucer, Wake Forest Univ. (United States); Gregory A. Bizarri, Lawrence Berkeley National Lab. (United States); Sebastien Kerisit, Fei Gao, Pacific Northwest National Lab. (United States); Pijush Bhattacharya, Eugene Tupitsyn, Emmanuel Rowe, Vladimir Buliga, Arnold Burger, Fisk Univ. (United States)

Various models of nonproportional response in scintillators have highlighted the importance of parameters such as branching ratios, carrier thermalization times, diffusion, kinetic order of quenching and associated rate constants, and radius of the electron track. For example, the fraction ηeh of excitations that are free carriers versus excitons was shown by Payne et al to have strong correlation with the shape of electron energy response curves from Compton-coincidence studies. Rate constants for nonlinear quenching are implicit in almost all models of nonproportionality, and some assumption about track radius must invariably be made. Diffusion, affecting time-dependent track radius and thus density of excitations, has been implicated as an important factor in nonlinear light yield, and several groups have recently highlighted diffusion of hot electrons in addition to thermalized carriers and excitons in scintillators. However, experimental determination of many of these parameters in the insulating crystals used as scintillators has seemed difficult. Subpicosecond laser techniques including interband z scan light yield, fluence-dependent decay time, and transient optical absorption are now yielding experimental values for several of the rates and ratios needed for modeling scintillator response. First principles calculations can fill in additional parameters still unavailable from experiment. As a result, quantitative modeling of scintillator electron energy response from independently determined material parameters is becoming possible in a small but growing number of materials. This paper describes our recent laser experiments, calculations, and numerical modeling of scintillator response. Supported by NNSA, Office of Nonproliferation Research and Development (NA-22) contracts DE-NA0001012 and DE-AC02-05CH11231.

8852-21, Session 5

Photosensor characterization for the Cherenkov Telescope Array: SiPM vs MAPMT

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The Cherenkov Telescope Array (CTA) is an advanced facility for ground-based gamma-ray astronomy which is currently in its preparatory phase. Using an array of optical telescopes deployed over >1 km^2, CTA will detect flashes of Cherenkov light from electromagnetic showers originating from the interaction of GeV-TeV gamma rays with the Earth's atmosphere. The telescope cameras consist of hundreds to thousands of fast photosensors to discriminate gamma-ray showers from the unavoidable light of the night sky background.

It is envisioned that the array will be partly composed of telescopes using a Schwarzschild-Couder two mirror design which has never been built before. With its improved optics compared to the conventional Davies-Cotton design, the Schwarzschild-Couder design will allow larger field of view with smaller pixel and camera size opening the door to new types of photodetectors in the field of gamma-ray astronomy.

In this talk, we will present an extensive and detailed study of the two most promising devices being considered for this telescope design: silicon photomultipliers and multianode photomultiplier tubes. We evaluated the most critical performance characteristics for imaging gamma-ray showers: photo-detection efficiency, cross-talk, dark noise, pulse shape, afterpulsing, temperature dependence, and aging. We present our results in a cohesive manner to clearly evaluate the advantages and disadvantages that both types of device have to offer in the context of GeV-TeV gamma-ray astronomy.

8852-23, Session 5

A hybrid detecting system based on position sensitive scintillation detector and HPGe detector

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In the last years great attention is paid on segmented HPGe detectors as a powerful tool for gamma-spectroscopy of exotic nuclei and gamma imaging. The measurement technology relies on pulse shape analysis followed by tracking of the photon interactions inside the detector [1], [2]. Such an approach requires very large number of electronics channels, each one connected to the corresponding segment, resulting in an enormous complexity of the apparatus.

For some gamma-spectroscopy applications as e.g. in-beam spectroscopy at high beam energies, where the Doppler correction of the photon energy deposited in the detector is crucial, or the gamma-camera, where the granularity of the front detector is of paramount importance, another less complex detection approach has been studied. It is based on a hybrid telescope-like system of a scintillation detector (Scatterer) and an HPGe detector (Absorber). The first photon interaction, most likely Compton scattering, occurs with high probability in the front placed position sensitive scintillation detector [3] and the scattered photon enters an HPGe crystal placed behind where its absorption is expected. The coincidence of these two events determines an useful event whose energy is the sum of the energy deposited in the both detectors. By using of a modern scintillation material as LaBr, CeBr or SrI, the good energy resolution of the HPGe detector will not be severely destroyed at the same time the position resolution of the Scatterer would enable Doppler correction. Additionally, fast timing may be achieved.

We studied experimentally by coincidence scanning technique [4] and by simulations the performance of such a hybrid detecting system. Special attention has been paid on the scintillation detector performance and its optimization, e.g. the detector thickness and the self-activity problem. The results of this study and the ongoing analysis and optimization of the system will be presented.

8852-24, Session 6

Effect of inclusions on thermal neutron detection with a semiconducting 6LiInSe2 crystal *(Invited Paper)*

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Chalcopyrite semiconductors such as 6LiInSe2 potentially can be used as efficient alternatives to gas or scintillator thermal neutron detectors. Including a neutron absorber (6Li) into the regular stoichiometry of a bulk semiconductor increases the detection volume compared to layered detector. 6LiInSe2 crystals were synthesized from enriched 6Li metal which was chemically purified to 99.999% and grown by the Vertical Bridgman method. A single crystal of 12.8 mm diameter and 1.98 mm thickness has successfully detected a series of alpha, gamma, and thermal neutron signatures. 6LiInSe2 crystals have high resistivity (>10^12 Ω*cm); however, many inclusions are present. Laser induced breakdown spectroscopy and IR microscopic studies have been undertaken to determine the composition and orientation of these inclusions. Subsequent optimization of crystal growth has been undertaken to improve upon inclusion concentrations and thereby improve charge collection in a detector. Radiation measurements were conducted on these improved crystals.

8852-25, Session 6

Solid-state thermal neutron detectors based on hexagonal boron nitride epilayers

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Boron-10 isotope has a capture cross-section of 3840 barn for thermal neutrons (with 0.025 eV energy), which is orders of magnitude larger than many isotopes. Hexagonal boron nitride (hBN) semiconductor epitaxial films have been synthesized by metal organic chemical vapor deposition. Thermal neutron absorption lengths have been measured to be about 238 µm and 67 µm for natural and 10B enriched hBN epilayers, respectively.

Neutron detectors were fabricated from hBN epilayers. Systematic studies were carried out on the correlation between the material growth conditions, carrier mobility-lifetime product, dark current and the neutron detector performance. Excellent performance of hBN neutron detectors has been demonstrated through high thermal neutron conversion efficiency, low leakage current, and low operating voltages. At room temperature, the leakage current (or dark current) density of hBN detectors is about 10^-11 A/cm^2 at a bias voltage of 10 V [1].1 A continuous irradiation with a thermal neutron beam generated an appreciable steady current response in hBN detectors, corresponding to an effective conversion efficiency approaching ~80% for absorbed neutrons [2]. Radiation damage to the hBN neutron detectors is being assessed by subjecting the devices to a prolonged irradiation by the 252Cf source and the results will be reported. Our results indicate hBN neutron detectors have the potential to replace He-3 gas detectors, which faces the very serious issue of He-3 gas shortage.

[1] J. Li, S. Majety, R. Dahal, W. P. Zhao, J. Y. Lin, and H. X. Jiang, “Dielectric strength, optical absorption, and deep ultraviolet detectors of hexagonal boron nitride epilayers,” Appl. Phys. Lett. 101, 171112 (2012).

[2] J. Li, R. Dahal, S. Majety, J.Y. Lin, and H.X. Jiang, “Hexagonal boron nitride epitaxial layers as neutron detector materials,” Nuclear Inst. and Methods in Physics Research Section A 654, 417 (2011).

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8852-27, Session 7

Spectral resolution in pixel detectors with single-photon processing *(Invited Paper)*

Christer Frojdh, Mid Sweden Univ. (Sweden)

Pixel detectors based on photon counting or single photon processing are becoming popular for spectral X-ray imaging. The detector is based on deep submicron electronics with functions to determine the energy of each individual photon in every pixel. The system is virtually noiseless when it comes to the number of the detected photons. However noise and variations in system parameters affect the determination of the photon energy.

Several factors affect the energy resolution in the system. In the readout electronics the most important factors are the threshold dispersion, the gain variation and the electronic noise. In the detector contributions come from charge sharing, variations in the charge collection efficiency and the statistical nature of the charge generation, as described by the Fano factor.

The MEDIPIX technology offers a powerful tool for investigating these effects since energy spectra can be captured in each pixel. In addition the TIMEPIX chip, operating in Time over Threshold mode, offers an opportunity to analyze individual photon interactions, thus addressing charge sharing and fluorescence. Effects of charge sharing and the properties of charge summing are investigated using MEDIPIX3RX. Experiments are performed using both Si and CdTe detectors operating in hole collection and electron collection mode.

In this paper we discuss the various contributions to the spectral noise and how they affect detector response. The statements are supported with experimental data from MEDIPIX-type detectors.

8852-28, Session 7

Zn effects on the reconstructions of the Cd-terminated CdTe (111) surface

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Cadmium telluride (CdTe) and cadmium zinc telluride (CZT) are known to have great potential in room-temperature X-ray and gamma ray semiconductor detector applications. Besides the quality of bulk crystal, the quality of the CdTe (CZT) surfaces and interfaces are often the dominant factors influencing the detector performance. Various surface reconstructions have been observed by experiments which remain controversial. Our previous theoretical study demonstrated that the most stable structure of Cd-terminated CdTe (111) A surface is the (2?2) reconstruction at high temperatures corresponding to the surface cadmium-vacancy model and the (√3x√3)R30° reconstruction is not stable for the pure CdTe (111) A surface [1]. However, we found that the Zn alloy can change the relative stability of surface reconstructions of CdZnTe (111) A surface. In this work, we studied the the phase transitions between (2?2) to (√3x√3)R30° reconstruction by employing ab initio thermodynamics calculations. The mechanism of the transition is the large local deformation and the surface relaxation induced by Zn. Our theoretical study has explained the experimentally observed (√3x√3)R30° reconstruction for the Cd0.96Zn0.04Te alloyed surface.

8852-29, Session 7

Development of a high-performance detection system for the hard x-ray astronomy (1-200 keV) based on a germanium double-sided strip detector

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The development of a high purity germanium (HPGe) double sided strip detector prototype for X-ray astronomy is presented. The proposed design will cover energies between 1 and 200 keV, and consists of a 4x4x1cm bulk with contacts on each side orthogonally segmented into 100 strips of a width of 350µm, with 50µm of gap between strips. Both spectrometry and imaging capabilities have been taken into account in the design of the detector: on one hand, the use of germanium guarantees high spectral resolution; on the other hand, finely segmented contacts provide high sensitivity on the position determination in the plane of the detector. In addition, the depth of the interaction can be estimated by looking at the difference of pulse raise time between the anode and the cathode. Pulse shape analysis and advanced algorithms are used for this purpose, obtaining a three-dimension localization of the point of impact of the photons. Furthermore, multiple interaction occurring simultaneously can be located, which makes the detector a suitable instrument for polarization measurements. The detection system relies on the extensive use of digital signal processing, with an early sampling of the signal at the output of the charge amplifier. This paper presents the measurement chain, including the detector itself, the electronic readout system and the signal processing methods that have been used. The main results of the laboratory tests carried out at this stage are presented, and finally the observed performances of the detector are discussed.

8852-30, Session 7

New modification of xenon gamma-ray detector with high-energy resolution

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The results of the development of the new modified xenon gamma-ray detector (XGD) are presented. This detector differs from the previously created ones in improved energy resolution ((1.7±0.1) % at 662 keV) and ability to work in hard acoustic conditions (up to 100 dB) practically without changes of spectrometric characteristics. These results have been achieved by developing a digital method of processing of each electric signal from XGD. On the basis of this method the digital electronics based on FPGA have been created.

The new gamma-ray detector can be widely used for different fundamental and applied tasks such as ecological radiation monitoring, nuclear reactor control, countering nuclear terrorism, radiation customs control, etc. In particular it is planned to use this device onboard unmanned aircraft vehicles for ecological monitoring of areas close to nuclear industry objects. Furthermore, XGD is included into the scientific equipment of the spacecraft "Interheliozond", which will approach the Sun to a distance of its 60-70 radiuses along a spiral trajectory.

8852-31, Session 7

Metal contacts on chemo-mechanically polished CdZnTe for radiation detector applications

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Advanced radiation detectors with high gamma-ray energy resolution, linear energy response and the capability of room temperature operation in both normal counting and spectroscopic modes are highly desirable for many applications such as medical diagnostics, non-destructive industrial evaluation, homeland security and counter-terrorism inspections, as well as non- or counter-proliferation detection to ensure national and international nuclear safety. State-of-the-art room temperature, high resolution x-ray and gamma-ray detectors are usually based on CdZnTe semiconductors. The structural and electronic properties of CdZnTe surfaces, especially surface/contact metal interfaces, have a significant impact on radiation detector performance, such as leakage current, signal to noise ratio and energy resolution, especially for relatively soft x-ray photons and large pixilated arrays. Atomically smooth and defect-free surfaces are desirable for high performance CdZnTe-based detectors; chemo-mechanical polishing is typically preformed to produce such smooth CdZnTe surfaces. We present a detailed study on the structural and electronic properties, and hence detector performance, of various metal contacts on chemo-mechanically polished CdZnTe surfaces of about 1 nm roughness. The surface morphology and surface electronic properties were studied with atomic force microscopy and x-ray photoelectron spectroscopy (XPS), and devices with current voltage (I-V) measurements and energy resolution analyses. XPS results indicate that the as-polished and metal-contacted surfaces are not stoichiometric. I-V measurements show either ohmic or rectifying behaviour depending on the contact metal and deposition procedures.

8852-32, Session 8

Optical design and signal processing for high-resolution gamma spectroscopy with large-volume scintillator detectors *(Invited Paper)*

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This presentation will describe the challenges of large volume scintillator detector design for high energy resolution gamma spectroscopy. Surface finish, optical geometry and diffuse reflector optimization can be implemented for improved readout with analog electronics. In addition, for scintillator materials that exhibit light-trapping (scintillation emission is re-absorbed and re-emitted prior to detection), digital scintillation trace acquisition and processing can be employed to improve the energy resolution for large volume scintillators. Europium-doped Strontium Iodide and Bismuth-loaded plastics in 3-15 in3 sizes will be presented as example scintillators amenable to this approach.

Acknowledgements

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8852-33, Session 8

Analysis of scintillator crystal production via the edge-defined film-fed growth method

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A model of edge-defined film fed (EFG) crystal growth is developed to study melt growth of cylinders of the scintillator crystal cesium iodide (CsI). This system is characterized by strongly nonlinear interactions of heat transfer, capillarity, and die geometry that give rise to multiple solution states under a single set of operating conditions. Purely capillary instabilities are identified that result from the interaction of surface tension with gravity. These give rise to two solution families distinguished by a difference in gap width between die face and growth interface. The narrow gap solutions are shape stable, and the wide gap solutions are shape unstable, though these can be stabilized by heat transfer similar to Czochralski growth. Additionally we identify several instabilities of convective heat transfer, which generally are of two types. One type is mostly convective in nature and largely independent of the interface or meniscus shapes. The other type is characterized by a strong interaction of convection with the geometry of the growth interface. Stronger convection moves the interface to a higher position, forming a larger gap. The larger gap allows a stronger flow to form, which enhances convection. This reinforcing behavior enables a family of solutions to exist in which the growth interface shape is concave in the central region, though it is convex elsewhere.

8852-34, Session 8

GYGAG(Ce) detector array with silicon photodiode readout

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Cerium doped GYGAG, (Gd,Y)(Ga,Al) Garnet, scintillators offer high light yields of ~50,000 Ph/MeV for high energy resolution, relatively high density of 5.8 g/cm3 for good stopping power and high Zeff of 48 for good photoelectric absorption. However, GYGAG(Ce) emission is centered in the green at ~550 nm, resulting in poor quantum efficiency of ~10% with typical photomultiplier tubes (PMTs). Fortunately, the longer wavelength emission couples well to Si photodiodes, offering quantum efficiency of ~80% in the green-red range. Further, photodiodes are smaller, lighter and more rugged than typical PMTs.

In order to minimize dark current, small area (3mm x 3mm) photodiodes are used. Using an array of small (3mm x3 mmx 6mm) GYGAG scintillators maintains the good resolution of GYGAG while allowing larger volumes of material to be used. We report here on our progress in engineering high resolution (<4% at 662 keV), low-power, lightweight GYGAG-Si photodiode arrays for hand held radioisotope identification devices (RIID's).

8852-35, Session 8

Temperature behavior of CLYC/MPPC detectors

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Current radiation detection systems rely on He-3 tubes for thermal neutron detection. He-3 tubes are popular due to their good performance, simplicity and good intrinsic gamma-ray discrimination. Due to low stockpiles of He-3 gas and increased prices many manufacturers are looking to replace these detectors in their instrumentation. Since fissioning materials emitting neutrons are rare, detection of any neutrons above the natural background is a strong indication of special nuclear materials presence.

In order to meet the need of a replacement for He-3 detectors, during the last year we have been developing a detector based on the combination of Cs2LiYCl6 (CLYC) scintillator and a Multi-Pixel Photon Counter photo-detector (MPPC). CLYC offers efficient thermal neutron detection, excellent discrimination between gamma rays, and gamma-ray energy resolution. The detection efficiency of 1 cm3 of Li-6 enriched CLYC is more than twice as high as the same volume of He-3 at 8 atmospheres. Discrimination between gammas and neutrons is achieved through pulse height and pulse shape analysis. CLYC/MPPC detectors can also be used to detect gamma rays. These properties and a small size of overall detector not only make it a very promising He-3 tube replacement, but provide added capability not found in He-3 detectors.

In this presentation, we report on temperature dependencies of a CLYC/MPPC detector in the range of -20C to 50C (ANSI N42.34-2006) expected from hand-held instrumentation. This includes the changes in pulse height spectra, energy resolution for the gamma and neutron peaks, and pulse shape discrimination.

8852-36, Session 8

GaN as an ultrafast robust scintillator

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We propose to use GaN as an ultrafast and robust scintillator for radiation detection. We have measured GaN photoluminescence spectral profile, which is centered at 365-369 nm [1]. Other groups have measured the GaN scintillation efficiency be 1E6 photons per MeV. We have also demonstrated the extreme proton radiation hardness of AlGaN/GaN optoelectronics devices [2, 3]. The AlGaN UV LED and UV photodiodes maintained their optical output or response up to 3E12 protons per square centimeter, which is equivalent to even better neutron radiation hardness. Further, GaN carrier relaxation time can be subpicoseconds, in both GaN material and quantum well structure. Currently we are working towards more detailed characterization of GaN optical photoluminescence using tunable ultrafast lasers, and GaN particle scintillation properties using neutron sources. This presentation will give an overview of our efforts.

[1] Ke-Xun Sun, Nevada Test Site Directed Research and Development Report, 2008.

[2] Ke-Xun Sun et al, "UV LED operation lifetime and radiation hardness qualification for space flights," J. Phys. Conf. Ser. 154 (2009) 012028.

[3] Ke-Xun Sun, "Applications of Robust, Radiation Hard AlGaN Optoelectronic Devices in Space Exploration and High Energy Density Physics," Invited Talk presented at CLEO 2011, Baltimore, Maryland, USA, May 2011

8852-37, Session 9

Understanding fundamental mechanisms of nonproportionality in inorganic scintillators

(Invited Paper)

Fei Gao, Sebastien Kerisit, Yulong Xie, Micah Prange, Luke W. Campbell, Renee Van Ginhoven, Pacific Northwest National Lab. (United States)

We will review recent progress on computational approaches to understand the fundamental mechanisms that give rise to nonproportionality in inorganic scintillator materials. First, we will discuss Monte Carlo simulations of gamma-ray interaction with SrI2 and LaBr3, two promising scintillator materials, and resulting predictions of important intrinsic properties that include W (the mean energy required to create an e-h pair), the Fano factor, and maximum theoretical light yield as a function of incident energy. It is of interest to note that the photon energy at which W becomes constant is about 150 eV in SrI2, while it is about 2 keV in LaBr3 and 10 keV in CsI. This suggests that the light yield of SrI2 is nonlinear only at very low incident energies, which is consistent with experimental observations and in contrast to CsI in which the initial rise in the relative light yield with increasing incident energy extends up to a few keV. Furthermore, the distribution of electron-hole pairs in SrI2 shows a linear track behavior, while it is clustered along the tracks in LaBr3, which give rise to regions of high excitation density along the ionization track in LaBr3. Also, it is observed that most electron-hole pairs are produced by interband transitions in SrI2, but a significant number of electron-hole pairs are created by plasmon excitations (in addition to interband transition) in LaBr3. This increase in the number of effective energy loss channels may lead to nonproportionality at higher energies in LaBr3, as compared to that in SrI2.

Second, we will discuss recent kinetic Monte Carlo (KMC) simulations of nonlinear quenching in CsI, CsI(Tl) and NaI(Tl). In these simulations, the interactions between STEs are described via dipole-dipole Förster transfer and are parameterized using experimental data on the excitation density dependent light yield following ultraviolet excitation. The KMC simulations reveal that nonlinear quenching occurs very rapidly (within a few picoseconds) in the early stages of the scintillation process. In addition, the KMC simulations enable us to compare and contrast the extent and mechanism of nonlinear quenching in CsI(Tl) and NaI(Tl), whereby mixed second/third quenching is observed for the former whereas pure second order quenching is found for the latter at 5.9-eV excitation. Finally, the ability of the KMC model to reproduce available experimental data allows for elucidating the elementary processes that give rise to the kinetics and efficiency of scintillation observed experimentally for a range of conditions.

8852-38, Session 9

Growth and characterization of CdTeSe for room-temperature radiation detector applications

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The ternary compound CdTexSe1-x can be a good choice for room-temperature radiation detector applications. The compound has several advantages over CdZnTe, particularly the near unity segregation coefficient of Se in CdTe, which ensures axial and radial compositional uniformity of the grown ingots. The ability to obtain larger and more uniform detector-grade crystals has the potential to drastically reduce the production cost of detectors compared to CdZnTe. In the present paper we will discuss the growth and characterization of CdTexSe1-x crystals and offer some preliminary results on device properties.

8852-39, Session 9

Bulk growth of uniform and near stoichiometric cadmium telluride

Santosh K. Swain, Sachin Bhaladhare, Amlan Datta, Kelvin G. Lynn, Washington State Univ. (United States)

Non-stoichiometry related extended defects in CdTe/CZT, such as tellurium inclusions and precipitates are known to be detrimental bulk defects in both detector grade and mercury cadmium telluride substrate grade materials. Conventional approaches to maintain or restore crystal stoichiometry rely on the use of a separate Cd reservoir integrated to the ampoule and maintaining an appropriate temperature field near the source or post growth thermal treatment in Cd/CdZn environment. We prove that it is possible to grow inclusion (secondary phases > 1 micron) free bulk CdTe in a cost-time effective way without post growth processing or requiring any ampoule and furnace modifications. As part of a systematic approach to eliminate these defects, undoped bulk CdTe crystal growth was accomplished in a vertical Bridgman configuration. As grown wafers were characterized with respect to infrared transmission, foreign impurity concentration determined by glow discharge mass spectrometry (GDMS), and bulk electrical resistivity. Excepting for grain boundaries and twins, the wafers were found to be completely free of inclusions of sizes >1 micron and the distribution at different parts of the grown boule were found to be identical. Star shaped cadmium inclusions were observed at some places near middle section of the ingot. The samples tested from this ingot exhibited high bulk resistivity values of 108 to 109 ohm.cm, which was in conformity with the low density of nonstoichiometric defects. GDMS results indicated that the concentration of unintentional impurities were low enough for the electrical behavior to be explained uniquely on the basis of native defects.

8852-40, Session 9

Post-growth annealing of CdZnTe crystals: an analysis of defect-structures and opto-electronic properties

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In this work, we investigate post-growth annealing to improve the properties of CdZnTe (CZT) crystals. Defect structures and opto-electronic properties of as-grown and annealed CZT crystals are characterized by IR transmission microscopy, white X-ray beam diffraction topography, current-voltage measurements, and low-temperature photoluminescence spectroscopy. New results from recent low-temperature and long-term annealing experiments will be presented and discussed.

8852-41, Session 10

Trap level analysis in CdZnTe and CdMnTe by I-DLTS, PICTS, TEES, and PL

Ki-Hyun Kim, Pilsu Kim, Korea Univ. (Korea, Republic of); Rubi Gul, Aleksey E. Bolotnikov, Giuseppe S. Camarda, Anwar Hossain, Brookhaven National Lab. (United States); Anna Cavallini, Univ. degli Studi di Bologna (Italy); Jan Franc, Charles Univ. in Prague (Czech Republic); Ralph B. James, Brookhaven National Lab. (United States)

Charge trapping and recombination are typical effects in semiconductors and generally prevent the complete charge collection in an X- and gamma-ray detector. Several experimental techniques such as photo-induced thermally stimulated current (TSC), current transient spectroscopy (PICTS), thermo-electric emission spectroscopy (TEES), photoluminescence (PL) and current deep-level transient spectroscopy (I-DLTS) had been applied for the trap analysis of CdTe and CdZnTe (CZT) material. However, the assigned trap energy levels were not same all the time due to the different sample properties and/or the different measurement technique. In this paper, we will present trap levels analysis of CZT:In and CdMnTe:In (CMT:In) measured by four different technique with same samples.

8852-42, Session 10

X-ray Response of CZT detectors for high-flux applications

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Several CZT detectors were evaluated by using the Micron-scale X-ray Detector Mapping (MXDM) system of beamline X27B at National Synchrotron Light Source (NSLS) of Brookhaven National Laboratory (BNL). The uniformity of the X-ray response maps for fabricated detectors is indicative of the performance of the detectors for high flux applications. The results will elucidate the defects responsible for the observed non-uniformities.

8852-43, Session 10

Contact scaling to high-resistivity compensated Cd1-xZnxTe

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High resistivity semiconductors are essential for radiation detectors. The high resistivity in detector tailored semiconductors must be achieved by low concentration of free carriers rather than by low mobility. The semi-insulating resistivity implies semi-intrinsic charge carrier concentrations and it is seldom achieved by high material purity and crystalline perfection. In most cases a compensation mechanism is responsible for

the low material conductivity. Such is believed to be the case of wide bandgap II-VI compound semiconductors (CdTe, Cd1-xZnxTe, etc.). Depositing electrical contacts with reproducible macroscopic behavior remains challenging. Furthermore, detailed understanding of electrical contacts to such materials remains elusive.

In this study finite element calculations are used to investigate the contact scaling effects and surface states impact for various compensation mechanisms. The computation results shed light on the conditions inside the metal-semiconductor-metal (MSM) structures with various contacts. It is shown that the current-voltage dependence in the presence of the velocity saturation phenomena even for ideal Ohmic contacts become very dependent on the compensating level properties. In the case of Schottky contacts the deep levels properties strongly affect the current-voltage characteristics and the internal electric field distribution

8852-44, Session 10

Breakthrough development of large-volume high-performance cadmium zinc telluride radiation detector *(Invited Paper)*

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Latest development of Cadmium Zinc Telluride (CZT) radiation sensor grown by the traveling heater method (THM) is reported. Excellent detector performance, close to 1% energy resolution at 662 keV gammas at room temperature has been achieved on pixellated 20x20x15 mm3 CZT detector without spectral correction. Detector energy resolution reached 0.6% FWHM after depth of interaction (DOI) correction. This breakthrough of the technology has been achieved via our recent development in THM crystal growth in combination with our proven device fabrication technique. The achievement commends CZT as the material of choice for mass production of room temperature radiation detectors for applications in homeland security, medical imaging and space applications such as that used in Compton imaging (1).

REFERENCES

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8852-17, Session PWed

Developing a high-resolution x-ray imager using electron multiplying (EM) CCDs

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Applications at synchrotron facilities such as macromolecular crystallography and high energy X-ray diffraction require high resolution imaging detectors with high dynamic range and large surface area. Current systems can be split into two main categories: hybrid pixel detectors and scintillator-coupled Charge-Coupled Devices (CCDs). Whilst both have limitations, CCD-based systems (coupled to fibre-optics to increase imaging area) are often used in these applications due to their small pixels and the high resolution. Electron-Multiplication CCDs (EM-CCDs) are able to suppress the readout noise associated with increased readout speed offering a low noise, high speed detector solution. A previous pilot study using a small-area (8mm x 8mm) scintillator-coupled EM-CCD found that through high frame-rates, low noise and novel uses of photon-counting, resolution could be improved from over 80 um to 25 um at 2 fps. To further improve this detector system, the high speed readout electronic developed for “lucky imaging” by the Institute of Astronomy, Cambridge, UK, can be used alongside a fibre-optic taper and EM-CCD to create a “best of both worlds” solution consisting of the high resolution of a CCD, along with the low noise, high speed (high dynamic range) and large effective area of pixel detectors. This paper details the developments in the study and discusses the latest results and their implication on the system design.

8852-45, Session PWed

Direction-sensitive hand-held gamma-ray spectrometer

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A novel, light-weight, hand-held gamma-ray detector with directional sensitivity is being designed. The detector uses a set of multiple rings around two cylindrical surfaces, which provides precise location of two interaction points on two concentric cylindrical planes, wherefrom the source location can be traced back by back projection and/or Compton imaging technique. The detectors are 1.5 x 1.5 mm europium-doped strontium iodide (SrI2: Eu2+) crystals, whose light output has been measured to exceed 120,000 photons/MeV, making it one of the brightest scintillators in existence. The crystal’s energy resolution, less than 3% at 662 keV, is adequate enough to bridge the resolution gap between sodium iodide and cadmium zinc telluride. The emission of SrI2: Eu2+ is well-matched to both photomultiplier tubes and blue-enhanced silicon photodiodes. The solid-state photomultipliers used in this design (each 1.5 x 1.5 mm) are arrays of active pixel sensors (avalanche photodiodes driven beyond their breakdown voltage in reverse bias); each pixel acts as a binary photon detector, and their summed output is an analog representation of the total photon energy, while the individual pixel accurately defines the point of interaction. This article will discuss Monte Carlo simulations made to determine if segmented crystal and/or position-sensitive photomultiplier tubes will increase directional sensitivity. A simple back-projection algorithm involving cone-surface mapping was modeled. The back projection for an event cone is a conical surface defining the possible location of the source. The cone axis is the straight line passing through the first and second interaction points.

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8852-46, Session PWed

Design and construction of large-volume scintillation detector for pulsed neutron detection

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In this work, an NE-102 plastic scintillator has been chosen for neutron detection. The neutron energy deposition in any point of the detector has been calculated by MCNPX code, and then by using the light response curve of the scintillator the number of photons generated due to neutron energy deposition has been determined. Finally, light photon transport has been carried out by the OPTICS code, and the effect of detector surface paint on light collection has been investigated. Considering the paint effect, a 15x12x50 cm3 plastic scintillator cell was manufactured. After making the detector and calculating detector efficiency and comparing it with the results of simulations, the uniformity process can be observed between them. Then the large volume plastic scintillator detector is used for observing plasma focus neutron pulse as well as hard X-ray pulse. Because of the speed difference between produced neutrons and X-ray photons, if the detector is located in a proper

distance from the Plasma Focus, the neutron and X-ray pulses could be seen separately. Measurement results showed that 3.5 meters distance between the detector and the plasma focus is appropriate for observing neutron and X-ray pulses separately. A pulsed neutron and X-ray source in this experiment is a 2.5kJ Mather type plasma focus device (SBUPF1) in Shahid Beheshti University with average neutron flux~3x107[3].

8852-47, Session PWed

GHz hard x-ray imaging using fast scintillators

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GHz imaging technology will be needed at high-luminosity X-ray and charged particle sources. It is plausible to combine fast scintillators with the latest picosecond detectors and GHZ electronics for multi-frame hard X-ray imaging and achieve an inter-frame time of less than 10 ns. The time responses and light yield of LYSO, LaBr3, BaF2 and ZnO are measured using a MCP-PMT detector. ZnO is an attractive material for fast hard X-ray imaging based on GEANT4 simulations and previous studies, but the measured light yield from the samples is much lower than expected.

8852-48, Session PWed

Calculations of the energy dependence of the sensitivity for planar CdZnTe gamma-ray detectors

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Considerable variations in the charge-carrier transport properties lead to the necessity of individual calibrations for CdZnTe gamma-ray detectors. Experimental measurement of the detectors' sensitivity in the gamma-quantum energy range of 0.04-3 MeV requires at least 10 different gamma-ray sources as references. For determining the energy dependence of the sensitivity for CdZnTe-detectors via a Monte-Carlo method, it is necessary to first measure the electron and hole mobility-lifetime products in each detector. Both methods for the determination of sensitivity of CdZnTe gamma-ray detectors require a lot of time, especially for the calibration of the response for multi-detector arrays. We carried out a set of experiments, wherein it was determined that the energy dependence of the sensitivity for planar CdZnTe detectors in the gamma-quantum energy range of 0.04-3.0 MeV can be reconstructed based on the results of measurements of pulse-height distributions with Am-241, Cs-137 and Co-60 sources. The errors for the obtained approximation formulae are compared with detailed calculations of CdZnTe-detectors' sensitivity via a Monte-Carlo method. The maximum error of the approximation formulae in the gamma-quantum energy range between 0.3 and 0.4 MeV was determined. We considered conditions in which the error of the approximation formulae compared with detailed Monte-Carlo calculations does not exceed 10%. The calculated values of the sensitivity are verified with the results of measurements with Eu-152 and Ba-133 sources. The calculated dependencies of the sensitivity of CdZnTe-detectors on the energy of the gamma-quanta can be used for estimating the changes in the charge-carrier transport parameters due to the accumulation of radiation-induced defects.

8852-49, Session PWed

Reasons of low-charge collection efficiency in CdTe detectors with ohmic contacts

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The problems are analyzed caused by the limitation on operating voltage of CdTe-based X/gamma-ray detectors with ohmic contacts by a value not higher than 80-100 V for the crystal thickness of 1 mm. Electrical measurements at different temperatures show that a rapid increase in the leakage current with rising bias voltage is equivalent to the contribution of an additional temperature-independent current component. Such character of the temperature effect is evidence that an increase in the current at higher voltages is caused by tunneling of minority carriers through the potential barrier created at the crystal surface due to non-ideality of an ohmic contact. The tunneling nature of the excess current does not allow to increase the operating bias voltage of the detector with lowering operating temperature because this leads to a significant reduction of the leakage current only at low voltages but not at higher ones. Optimization of the formation of electrical contacts could make it possible to enhance charge collection, however increasing this indicator of detector (for example, up to 99% instead of present 5-6% for the best samples) is complicated because of a slow sub-linear increase in this factor with rising voltage. Calculations of the charge collection efficiency shows that success is possible by lengthening the charge carrier lifetime in CdTe up to 20-30 microseconds. This obviously will require a decrease in the concentration of deep impurities (defects) in the material that is impossible without addressing the issue of improving the quality of CdTe crystals.

8852-50, Session PWed

Differential thermal analysis investigation of Cd0.95-xMnxZn0.05Te alloys

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Cd0.95-xMnxZn0.05Te with x=0.05-0.25 were synthesized using a double-zone furnace and elemental starting materials. The melting Tm and crystallization Ts temperatures of Cd0.95-xMnxZn0.05Te alloys were determined by differential thermal analysis. The melting-crystallization rate was 5 and 10 K/min with a melt dwell time of 1, 10, 20 and 30 min. Experimental results showed that the melting temperature Tm decreased with increasing "x", and the crystallization temperature Ts increased with increasing "x". The crystallization rate dependencies vs. melt's crystallization temperature were studied. In most cases they decreased with the rise of the crystallization temperature, while the crystallization temperature decreased with decreasing melt dwell time. New results on this alloy will be presented.

8852-51, Session PWed

New neutron detector by using semiconductor BGaN

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Neutron imaging technology is expected as a new tool for non-destructive inspection system for high penetration into heavy metals. Therefore, a high speed and high resolution neutron detector is required for the neutron imaging technique. We have suggested a neutron detector by using semiconductor BGaN. We have considered BGaN which was an alloy of BN and GaN as having the sensitivity for the neutron, because the B atom which is able to capture neutron is contained in BGaN. Due to its poor gamma-rays sensitivity, GaN is used to distinguish neutrons from the background gamma-rays. In this work, we fabricated crystalline BGaN and we investigated its neutron detection properties.

BGaN was grown by metal organic vapor phase epitaxy (MOVPE) using the following precursors: trimethylgallium (TMG), triethylboron (TEB) and NH3 for Ga, B and N, respectively. The epitaxial films structure consisted in a GaN buffer layer and a BGaN layer onto a c-plane Al2O3 substrate.

Radiation detection properties were evaluated using the depletion layer formed by applying reverse bias voltage for the Schottky contact (Au/BGaN). Under neutron irradiation, the generated electrons are detected as electron signal. As a result, we confirmed that electrons were generated at the depletion layer for neutron irradiation. This was the detection signal for alfa-ray which are converted into neutrons by B atoms.

We can conclude that our proposed BGaN system can be successfully used as a neutron detector.

8852-52, Session PWed

Characterization of CdTe and (CdZn)Te detectors with different metal contacts

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CdTe and (CdZn)Te are very promising materials for room temperature X-ray and gamma-ray detectors with high charge collection efficiency (CCE). The amount of collected charge strongly depends on the internal electric field. The lower the electric field the less photo-generated carriers are collected as they are subject to trapping. One of the main problems of preparation of high performance detectors is still the formation of long-term stable contacts resulting in high charge collection efficiency with the absence of detector polarization. Detectors with ohmic contacts exhibit linear I-V characteristics and constant internal electric field without significant polarization. Detectors with one Schottky contact exhibit distortion of the internal electric field and enhanced polarization.

In this work various metal contacts (Au, In and Pt) with different methods of deposition (electroless deposition and evaporation) are prepared on the same detector and the I-V characteristics and transient-current technique (TCT) are used to characterize the quality of the contacts and spatial distribution of the internal electric field. TCT measurements were performed using a current-sensitive preamplifier and a broadband digital oscilloscope. Utilization of different metals enables us to prepare both ohmic and blocking (Schottky) contacts. 241Am ∞-particles with energy of 5.49 MeV were used to create electron-hole pairs close to the cathode. After processing of the recorded pulses the collected charge, carrier mobilities and the inner electric field distribution are evaluated. All measurements are compared with the CCE measurements using alpha particles and the single carrier Hecht equation.

8852-53, Session PWed

Raman analysis of Zn(1-x)Mn(x)Te polycrystalline films

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Zn1-xMnxTe solid solutions have attracted much attention as a promising material for applications in microelectronics due to their unique photoluminescence, magnetic and magneto-optical properties. However, even basic properties of Zn1-xMnxTe, such as optical and structural parameters, have not been studied systematically.

In this study Zn1-xMnxTe solid solution thin films were deposited on glass substrates by a close-spaced vacuum sublimation technique (CSVS) under the following growth conditions: evaporator temperature was 1073 K; substrate temperature was varied in the range from 423 to 823 K. A high-purity Zn1-xMnxTe powder (10% Mn concentration) was used as a charge for the evaporation. The Raman spectroscopy was performed by a Witec Alpha SNOM confocal microscope with 532-nm laser excitation at room temperature within the frequency range of 100-900 sm-1.

A number of intense lines at 176.5, 206, 416 and 621 cm-1 were observed in the Raman spectra. These lines were interpreted according to reference data as 1TO, 1LO, 2LO, and 3LO phonon modes. The presences of several phonon replicas in the Raman spectra confirm high crystal quality of the samples. The Mn concentration was estimated according to the shift in peak position in Raman spectra of the Zn1-xMnxTe films as compared with pure ZnTe. These results were also compared with the results obtained by energy dispersive X-ray analysis.

8852-54, Session PWed

The electrical properties of Al-doped CdTe crystals

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The behavior of aluminum dopants in II-VI compounds is similar to indium, and both of them can be used to obtain high-resistivity material for Cd(Zn)Te detectors. To understand better the influence of Al dopants on CdTe electrical properties, three ingots with different Al content (10^17-10^19 atoms/cm3) were grown by the Bridgman method. The ingots were cut into wafers, polished and etched. I-V curves and IR images were measured for every wafer. The dependences between the resistance and wafer location in the ingots were determined. The maximal transmittance and resistance were determined in the wafers from the ingot with Al content in the melt of approximately 5x10^18 atoms/cm^3.

8852-55, Session PWed

Detectors of ionizing radiation on the base of surface-barrier Ni-CdZnTe-Ni structure

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One of the ways to improve the charge collection in semiconductor X- and gamma-ray detectors is by increasing the electric-field strength. The limiting factor in this case is the amount of leakage current. It is possible to reduce it by forming a rectified Schottky contact instead of an Ohmic one. That allows the creation of a depletion layer in the semiconductor with an electrical resistance that is much larger than the bulk resistivity. In this case, the electromotive intensity increases 10-100 times. A surface-barrier structure on a semi-insulating Ni-CdZnTe-Ni crystal (n-type) with a resistivity of 10^10 Ohm-cm at room temperature was formed. The leakage current was measured to be less than 3 nA at 1500 V. Results on the properties of this detector structure will be discussed.

8852-56, Session PWed

Three-energy radiography method for uniformity control of composite materials including components with different effective atomic numbers

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A receiving-detecting circuit has been developed on the basis of “scintillator-photodiode” detector array with improved spatial resolution.

Tests of the receiving-detecting circuit have been carried out, obtaining shadow X-ray images for evaluation of characteristics of digital radiographic systems for non-destructive testing on its base.

Using high precision of positioning of the inspected object movement mechanism, one can successively obtain three images at three different anode voltages and different filtration conditions with subsequent combination of the three images obtained in different energy ranges.

Using this method, we have obtained three-energy X-ray images of silicon carbide plates impregnated with silicon used for fabrication of bullet-proof vests.

Non-uniform character of impregnation was noted, which substantially affects mechanical strength of the plates. Basic relationships were determined for reconstruction of the absorption coefficient energy dependence in three-energy radiography.

Using a three-coordinate RGB identification palette, differences in the effective number of different plates could be noted.

The three-energy image shows that it is higher amount of silicon, with its atomic number higher as compared with silicon carbide, that enhances the blue component of the RGB palette..

The obtained results lead to conclusion that three-energy radiography can be also used for studies of other multi-component and composite materials if their constituents have even small differences in the values of effective atomic number. Preliminary estimates show that the accuracy of detection of discrepancies is better than 10% for materials with Zeff ? 7.

8852-57, Session PWed

Gamma-ray nonvolatile sensor comparison between SONOS and SOTOS capacitor device

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The silicon-oxide-nitride-oxide-silicon (SONOS) and silicon-oxide-TEOS-oxide-silicon (SOTOS) capacitor devices can be candidates for nonvolatile gamma radiation sensors. In case of SONOS and SOTOS gamma radiation sensors, the gamma ray radiation induces significant decrease of threshold voltage. The changes of threshold voltage for SONOS and SOTOS after gamma ray expose can be correlated to the dose of gamma ray exposure as well. In this paper, the performance for SONOS and SOTOS capacitor type gamma ray sensor were compared. The SONOS capacitor device with ONO gate dielectric in this study has demonstrated the better feasibility for gamma ray dosimeter application.

EXPERIMENTAL

In this study, two kind of SIS gate dielectric SiO2- Si3N4- SiO2 (ONO) and SiO2- TEOS- SiO2 (OTO) were compared. We use Silane CVD SiO2-CVD Si3N4- Thermal SiO2 for ONO gate dielectric and Silane CVD SiO2-CVD TEOS- Thermal SiO2 for OTO gate dielectric. The thickness of gate dielectric for O-N-O/O-T-O structure is 50Å-200Å-50Å /50Å-200Å-50Å. In this paper, the changes of threshold voltage between SONOS & SOTOS after Gamma ray expose were compared. To write data on these SONOS and SOTOS capacity devices, gamma radiation was exposed and a positive gate voltage was applied on these SONOS and SOTOS capacity devices simultaneously. For the data read, the change of gate threshold voltage in this case can be correlated to the exposure dosage of Gamma radiation as well. These trapped charges can be always accumulated in gate dielectric layer, so dose record can’t be destroyed by data write and read. For the dosage data erase, data in these SONOS and SOTOS capacity devices can be erased to original null state by opposite charges injection.

RESULTS AND DISCUSSIONS

As illustrated in figure 5 it can be seen that the capacity to voltage curves (C-V curve) of SONOS shifted far to the left after 10 Mrad gamma ray irradiation. This implies that gamma ray radiation induces a significant decrease of threshold voltage for SONOS. The amount of decrease of threshold voltage is about 2 volts. It is considered that the change is due to significant increase of positive trapped charges in the gate dielectric ONO layer after gamma ray irradiation. From figure 6, it also can be seen that the capacity to voltage curves (C-V curve) of SOTOS shifted to the left after 10 Mrad gamma ray irradiation. The amount of decrease of threshold voltage is up to about 1 volts. The electron-hole pairs are generated throughout the insulation layers, when these SONOS and SOTOS capacity devices structure are irradiated by gamma rays. These free carriers are swept by electric field, and some of them are captured by the charge trap centers, especially at the O-N/O-T interface and S-O interface. As shown in experiment data, the change of threshold voltage for SONOS is more significant than that for SOTOS. The dependencies of threshold voltage shifts on radiation dose in ONO gate dielectric is more significant than the one in OTO gate dielectric. It can be explained that the amount of positive trapped charges in the ONO gate dielectric layer is greater than the one in the OTO gate dielectric layer; so the decrease of threshold voltage for SONOS is more significant than the one for

SOTOS. It is suggested that the amount of hole traps at O-N interface in ONO gate dielectric layer is more than the one in the OTO gate dielectric layer. As illustrated in figure 7 and figure 8, it also can be seen that the gate leakage current of SONOS after gamma irradiation are less than that of SOTOS. From figure 9 and figure 10, it also can be seen that the dependencies of the threshold voltage decrease on gamma radiation dose for SONOS received are more significant than that of SOTOS. The decrease of gate threshold voltage in this case can be correlated to the increase of positive trapped charges in the insulator and the increase of exposure dosage for Gamma radiation as well. As illustrated in Figure 11 and figure 12, It also can be seen that the threshold voltage decay of

SONOS after gamma irradiation is less than that of SOTOS. This capacity device with ONO gate dielectric in this study has demonstrated the better feasibility of using SONOS capacity device for Gamma Ray dosimeter.

8852-58, Session PWed

Radioluminescence dosimetry by scintillating fiber optics: the open challenges

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In the last decade, the interest in scintillating fiber optics for ionizing radiation monitoring is constantly increasing. Among the fields of possible applications of these sensors, radiation therapy represents a driving force for the research and development of new devices. In fact, the small dimensions of fiber optics based detectors, together with their real-time response, make these systems extremely promising both in quality assurance measurements of intensity modulated radiotherapy beams, and in in-vivo dosimetry. On the other hand, two specific aspects might represent limiting factors: (i) the "stem effect", that is the spurious luminescence originating as consequence of the irradiation of the light guide, and (ii) the "memory effect", that is the radioluminescence sensitivity increase during prolonged exposition to ionizing radiation, typical of many scintillating materials.

These two issues, representing the main challenges to face for the effective use of scintillating fiber as dosimeters in radiotherapy, were studied considering amorphous silica matrices prepared by sol-gel method and doped with various rare earths (i.e. Ce, Eu and Yb). The origin of the stem effect was investigated by means of spectral measurements of the doped fibers irradiated with X-rays and electrons of different energies, field sizes and orientations. New approaches for removing the stem effect on the basis of the radioluminescent spectral analysis and of optical filtering are presented and discussed. Furthermore, the causes and phenomenology of the memory effect are described, considering also the effect of dose accumulation with different dose rates and energies of ionizing radiation.

8852-59, Session PWed

Boron selenide semiconductors for thermal neutron counting

Alireza Kargar, Radiation Monitoring Devices, Inc. (United States)

Thermal neutron detectors in planar configuration were fabricated from B2Se3 (Boron Selenide) crystals grown at RMD Inc. All fabricated semiconductor devices were characterized for the current-voltage (I-V) characteristic and neutron counting measurement. Pulse height spectra were collected from 241AmBe (neutron source on all samples), as well as 137Cs and 60Co gamma ray sources. In this study, the resistivity of all crystals is reported and the collected pulse height spectra are presented for fabricated devices. Finally, the neutron detection of the B2Se3 detectors is compared with a standard 3He tube for further verification. Note that, the 241AmBe neutron source was custom designed with polyethylene around the source as the neutron moderator, mainly to thermalize the fast neutrons before reaching the detectors. The B2Se3 devices showed response to thermal neutrons of the 241AmBe source.

8852-60, Session PWed

Improved CZT detectors: innovative contacts and unique surface treatments

Krishna C Mandal, Ramesh M. Krishna, Sandeep K. Chaudhuri, Univ. of South Carolina (United States)

CZT (Cd0.9Zn0.1Te) gamma radiation detectors are presently the best candidates for room temperature operation. At present, the typical energy resolution of CZT detectors is ~1%, rather than the desired ≤0.5%. To achieve this energy resolution, we have employed bandgap engineered novel amorphous contacting techniques, unique post growth treatment, and surface modifications. The approach involved three innovative pathways to improve the resolution of CZT radiation detectors: (1) implementation of high-barrier Schottky contacts to reduce the leakage current to an acceptable level; (2) post growth annealing treatments to eliminate Te-inclusions, which trap the electrons and limit the signals observed in the external circuitry; and (3) surface passivation by unique surface modifying treatments to passivate electrically active surface states which in turn helps to reduce leakage current. Chemical treatment is a very effective method for passivation of semiconductor surfaces. Sulfides (Na2S, xH2O) and selenides (Na2Se, 9H20) pretreatments of Cd0.9Zn0.1Te have been shown to improve the interface properties of metal (M)/Cd0.9Zn0.1Te significantly. The interface state density as obtained from C-V (1 MHz) measurements was found to reduce to 1.2x10^10 from 4.8x10^10 cm^-2eV^-1after surface treatment. The reduced interface state density resulted in increased photoluminescence intensity. X-ray photoelectron spectroscopy studies revealed the formation of Te-S and Te-Se after sulfide and selenide treatments respectively, which are responsible for better interfacial behavior. Final assessments of the detector performance have been carried out using various radio-isotopes in the energy range of 60-662 keV. The improved CZT detectors are cost-effective and highly efficient, and offered substantial performance advantages.

8852-61, Session PWed

Characterization of amorphous selenium alloy detectors for x-rays and high-energy nuclear radiation detection

Krishna C. Mandal, Abhinav Mehta, Sandeep K. Chaudhuri, Univ. of South Carolina (United States); Yunlong Cui, Michael Groza, Arnold Burger, Fisk Univ. (United States)

Synthesized amorphous selenium (a-Se) alloy samples have been characterized for room temperature x-rays and high-energy nuclear radiation detector applications. The alloy composition has been optimized to ensure good charge transport properties and detector performance. The synthesis of a-Se (As, Cl) alloys has been carried out by thoroughly mixing zone-refined (ZR) Se (~7N) with previously synthesized a-Se(As) and a-Se(Cl) master alloys (MS). The synthesized alloys have been characterized by x-ray diffraction (XRD), glow discharge mass spectroscopy (GDMS), differential scanning calorimetry (DSC), Fourier transform infra-red spectroscopy (FTIR), x-ray photoelectron spectroscopy (XPS), temperature varying current-voltage (I-V) characteristics, capacitance-voltage (C-V) measurements, and thermally stimulated current measurements (TSC). Raman spectroscopy demonstrated that the a-Se(As) master alloy samples were in metastable monoclinic Se8 states, in which seven vibrational modes are located at 40(41), 59(60), 77, 110, 133, 227(228) and 251(252) cm^-1. However, a-Se(Cl) master alloy samples is in stable form of trigonal structure of Se8, in which two modes at 142 and 234 cm^-1 were found. Both Raman and energy dispersive spectroscopy (EDS) exhibited that a small amount of tellurium (Te) existed in a-Se(As,Cl) master alloy samples. DSC measurements showed that a-Se(Cl) MS and a-Se(As) MS samples have one melting point, located at ~219.6C, whereas a-Se-As (0.52%)-Cl and Se-As(10.2%)-Cl(60 ppm) both possess two melting points, located at 221 and 220.3C respectively. The a-Se alloy plate detectors have been fabricated and tested and the results showed high dark resistivity (10^12

- 10^13 ?-cm), good charge transport properties, and cost-effective large area scalability.

8852-62, Session PWed

THM-grown CdZnTe detectors

Shariar Motakef, Piotr Becla, Stacy Swider, Krzysztof Becla, Matthew R. Overholt, John Fiala, William Higgins, CapeSym, Inc. (United States)

Growth of CdZnTe at temperatures lower than the melting point temperature of the material offers two major advantages relative to solidification from melt. The first advantage is the increase in the segregation coefficient of most impurities, resulting in lower background impurities in the grown material. The second advantage is the possibility of growing single crystal boules, in contrast to boules produced by solidification from melt which generally contain a number of grains.

We report on growth of CdZnTe by the Travelling Heater Method (THM) method. We have established a repeatable process for growth of single crystals boules. The grown crystals have been subjected to post-growth processing to produce materials for radiation detectors. The detectors have a very low density of small Te precipitates of 1-2 microns in diameter and have high resistivity in the range of 109-1010 ohm-cm. The electron lifetime-mobility of detectors have a mean value of 0.9x10-2 cm2/V, with a variation of +/- 0.3x10-2 cm2/V. The energy resolution of planar detectors at high field strengths is in the range of 1.4-1.7%.

The point defect signature of the produced material has been investigated by Photo Induced Current Transient Spectroscopy. The detectors with superior ut are observed to have low concentration of midgap defects relative to the shallow defects.

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8852-63, Session PWed

Measurement of volatile components in iodine- and chlorine-based starting materials for scintillators and neutron detectors

Stacy Swider, William Higgins, Krzysztof Becla, Shariar Motakef, CapeSym, Inc. (United States)

Alkaline-earth binary and ternary halides can be made into bright scintillators when activated with Eu2+ or Ce3+. However the hygroscopic nature of starting material encourages the formation of oxy-halides and carbonates that ultimately lead to cracking and/or poor scintillation performance in the grown crystal. A similar degradation in structural integrity and performance is observed in CLYC crystals used for neutron and gamma detection. In order to develop protocols to minimize contamination, it is of interest to analyze the starting material for water, carbon dioxide, and other species adsorbed on the surface or contained in the bulk. We report on the evolution of volatile species in SrI2, EuI2, CsCl, LiCl YCl3, and CeCl3 when heated in vacuum. Measurements were made via residual gas analysis (RGA). The experiments consist of heating a small amount of the starting material under vacuum and recording the partial pressure of the evolving gases as the sample temperature is increased. We have observed two distinct regimes. First, release of adsorbed gases such as H2O and CO2 at temperatures up to 400 degC. The second regime coincides with the evaporation of iodine or chlorine, where other elements are released. The incongruent melting points and thermal behavior (dissociation, sublimation) of the binary components also pose considerable process challenges. Released elements vary among the materials studied, but generally include water, carbon dioxide, argon, sulfur, and certain chlorine species. These results provide guidelines for removal of adsorbed gases from the starting material, and suggest a need for stoichiometry control.

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8853-19, Session PWed

Tests of pixilated CZT detectors with slanted-hole collimators in a compact endocavity gamma camera

Yonggang Cui, Brookhaven National Lab. (United States); Terry Lall, Jim Ionson, Gamma Medical Technologies (Canada); Giuseppe S. Camarda, Anwar Hossain, Ge Yang, Utpal N. Roy, Ralph B. James, Brookhaven National Lab. (United States)

We will discuss test results for a small field-of-view endocavity gamma camera that uses CdZnTe pixilated detectors to detect and image gamma-ray sources. The camera uses collimators with slanted holes to obtain limited 3D imaging. A prototype system for planar imaging has already been developed and clinically evaluated, and a new version of the gamma camera is being assembled capable of providing depth information as well as planar images. A ML-EM method will be used for the 3D image reconstruction. Bench-top data using the prototype system with slanted collimators will be reported for sealed Co-57 sources.

8853-21, Session PWed

Impact of fano factor on position and energy estimation in scintillation detectors

Vaibhav Bora, Harrison H. Barrett, Ctr. for Gamma-Ray Imaging, College of Optical Sciences, The Univ. of Arizona (United States); Abhinav K. Jha, College of Optical Sciences, The Univ. of Arizona (United States); Eric W. Clarkson, Ctr. for Gamma-Ray Imaging, College of Optical Sciences, The Univ. of Arizona (United States)

No Abstract Available

8853-1, Session 1

Dark-count-less x-ray photon counting using a YAP(Ce)-MPPC detector and its application to computed tomography *(Invited Paper)*

Eiichi Sato, Yasuyuki Oda, Iwate Medical Univ. (Japan); Hajime Kodama, Osahiko Hagiwara, Hiroshi Matsukiyo, Akihiro Osawa, Toshiyuki Enomoto, Manabu Watanabe, Shinya Kusachi, The Toho Univ. (Japan); Shigehiro Sato, Akira Ogawa, Iwate Medical Univ. (Japan)

To develop a high-speed energy-dispersive X-ray CT, we performed investigation of dark-count-less X-ray photon counting using a YAP(Ce)-MPPC detector. YAP(Ce) crystal with a decay time of 30 ns is stuck on the light-receiving surface of a multipixel photon counter (MPPC) and covered with an aluminum cap with a 0.2 mm-thick aluminum window. Successively, the detector is shielded using an aluminum case and a BNC connector, and the anode electrode of the MPPC is connected to the ground. The photocurrent from the MPPC was amplified by a high-speed current-voltage amplifier, and the event pulse is sent to a multichannel analyzer (MCA) to measure X-ray spectra. The MPPC was driven in pre-Geiger mode at a bias voltage of the MPPC of 70.7 V. Photon-counting computed tomography (PC-CT) is accomplished by repeated linear scans and rotations of an object, and projection curves of the object are obtained by the linear scan. In the PC-CT, we confirmed energy-dispersive effect with changes in the lower level voltage of the event pulse.

8853-2, Session 1

Energy dispersive photon counting detectors for breast imaging *(Invited Paper)*

William C. Barber, DxRay, Inc. (United States); Jan C. Wessel, Nail Malakhov, Gregor Wawrzyniak, Interon AS (Norway); Neal E. Hartsough, Thulasidharan Gandhi, DxRay, Inc. (United States); Einar Nygard, Interon AS (Norway); Jan S. Iwanczyk, DxRay, Inc. (United States)

We report on our efforts toward the development of silicon (Si) strip detectors for energy-resolved clinical breast imaging. Typically, x-ray integrating detectors based on scintillating cesium iodide CsI(Tl) or amorphous selenium (a-Se) are used in most commercial systems. Recently, mammography instrumentation has been introduced based on photon counting silicon Si strip detectors. Mammography requires high flux from the x-ray generator, therefore, in order to achieve energy resolved single photon counting, a high output count rate (OCR) for the detector must be achieved at the required spatial resolution and across the required dynamic range for the application. The required performance in terms of the OCR, spatial resolution, and dynamic range must be obtained with sufficient field of view (FOV) for the application thus requiring the tiling of pixel arrays and scanning techniques. Room temperature semiconductors, operating as direct conversion x-ray sensors, can provide the required speed when connected to application specific integrated circuits (ASICs) operating at fast peaking times with multiple fixed thresholds per pixel, provided that the sensors are designed for rapid signal formation across the x-ray energy ranges of the application at the required energy and spatial resolutions. We present our methods and results from the optimization of prototype detectors based on Si strip structures. We describe the detector optimization and the development of ASIC readout electronics that provide the required spatial resolution, low noise, high count rate capabilities and minimal power consumption.

8853-3, Session 1

Characteristics of a ceramic-substrate x-ray diode and its application to computed tomography

Manabu Watanabe, The Toho Univ. (Japan); Eiichi Sato, Iwate Medical Univ. (Japan); Hajime Kodama, Osahiko Hagiwara, Hiroshi Matsukiyo, Akihiro Osawa, Toshiyuki Enomoto, Shinya Kusachi, The Toho Univ. (Japan); Shigehiro Sato, Toho Univ. School of Medicine (Japan); Akira Ogawa, Iwate Medical Univ. (Japan)

X-ray photon counting was performed using a silicon X-ray diode (Si-XD) at a tube voltages ranging from 40 to 110 kV. The Si-XD is a high-sensitivity Si photodiode selected for detecting X-ray photons, and X-ray photons are directly detected using the Si-XD without a scintillator. Photocurrent from the diode is amplified using charge-sensitive and shaping amplifiers. To investigate the X-ray-electric conversion, we performed the event-pulse-height (EPH) analysis using a multichannel analyzer (MCA). Using an americium-241 (241Am) ?-photon source with an energy of 59.5 keV, the photon count substantially increased with decrease in the channel number of the MCA. Photon-counting computed tomography (PC-CT) is accomplished by repeated linear scans and rotations of an object, and projection curves of the object are obtained by the linear scan. In PC-CT at a constant tube voltage, we observed image-contrast variations with changes in lower-level voltage of the event pulse using a comparator.

8853-4, Session 1

Investigation of x-ray photon counting using a silicon-PIN diode and its application to energy-dispersive computed tomography

Hajime Kodama, The Toho Univ. (Japan); Eiichi Sato, Michiaki Sagae, Iwate Medical Univ. (Japan); Osahiko Hagiwara, Hiroshi Matsukiyo, Akihiro Osawa, Toshiyuki Enomoto, Manabu Watanabe, Shinya Kusachi, The Toho Univ. (Japan); Shigehiro Sato, Toho Univ. School of Medicine (Japan); Akira Ogawa, Iwate Medical Univ. (Japan)

X-ray photon counting was performed using a readymade silicon-PIN X-ray diode (Si-PIN-XD) at tube voltages ranging from 50 to 100 kV. The Si-PIN-XD is a high-sensitivity Si-PIN photodiode selected for detecting X-ray photons, and X-ray photons are directly detected using the 100 MHz Si-PIN-XD without a scintillator. Photocurrent from the diode is amplified using charge-sensitive and shaping amplifiers. Using a multichannel analyzer (MCA), X-ray spectra at a tube voltage of 100 kV could easily be measured. The photon-counting computed tomography (PC-CT) is accomplished by repeated linear scans and rotations of an object, and projection curves of the object are obtained by the linear scan. In the PC-CT, we confirmed the energy-dispersive effect with changes in lower-level voltage of the event pulse using a comparator.

8853-5, Session 2

Application of high-space bandwidth detectors in microSPECT *(Invited Paper)*

Roel Van Holen, Univ. Gent (Belgium)

No Abstract Available

8853-6, Session 2

SmartCAM: an adaptive clinical SPECT camera

Christopher Dumas, Adam Bernstein, Kevin Lewis, Matt Nipper, Donovan Morgan, Alonzo Espinoza, The Univ. of Arizona (United States); Harrison H. Barrett, Matthew A. Kupinski, Lars R. Furenlid, College of Optical Sciences, The Univ. of Arizona (United States)

No Abstract Available

8853-7, Session 2

Design and characterization of low-noise multichannel front-end readout ASICs dedicated to CZT detectors for biomedical imaging applications *(Invited Paper)*

Wu Gao, D. Gao, T. Wei, B. Gan, H. Zeng, R. Zheng, Y. Hu, Northwestern Polytechnical Univ. (China)

This talk is on the design techniques of low noise multi-channel front-end readout application-specific integrated circuits (ASICs) for biomedical imaging applications such as PET, SPECT, CT etc. In this presentation, three parts will be included. Firstly, research progresses in analog signal readout and processing, A/D converters and digital signal pre-processing techniques will be given. Moreover, the test results of our four developed ASICs will be presented and discussed in the second part. Thirdly, the conclusions and prospects of low-noise front-end readout ASICs will be described.

8853-8, Session 2

A SPECT imager with synthetic collimation

Ronan J. Havelin, National Univ. of Ireland, Galway (Ireland); Harrison H. Barrett, College of Optical Sciences, The Univ. of Arizona (United States); Brian W. Miller, Pacific Northwest National Lab. (United States); Lars R. Furenlid, College of Optical Sciences, The Univ. of Arizona (United States); J. Mary Murphy, Mark J. Foley, National Univ. of Ireland, Galway (Ireland)

A multi-pinhole SPECT system was designed to produce synthetic-collimator images of a small field of view. A focused multi-pinhole collimator was constructed using rapid-prototyping and casting techniques. The collimator projects the center of the field of view through forty-six pinholes when the detector is adjacent to the collimator. The detector is then moved further from the collimator to increase the magnification of the system. The amount of pinhole projection overlap increases as the system magnification increases. There is no rotation in the system; a single tomographic angle is used in each system configuration. The complexity of the multi-pinhole collimator requires the use of an iterative reconstruction algorithm. To reconstruct an activity distribution, iterative algorithms require an accurate model of the system response. A low-resolution system response is measured by translating a point source through a coarse grid encompassing the field of view, for each configuration. The pinhole projections are individually identified and associated with their respective apertures. A 2D elliptical Gaussian model is applied to the pinhole projections on the detector. These coefficients are associated with the object-space location of the point source, and a finer system matrix is interpolated. The interpolation is validated through comparison with a small, high-resolution system matrix that is experimentally measured. The system is also validated experimentally with a hot-rod phantom. The average spatial resolution of the system along each axis is estimated using the Fourier crosstalk matrix.

8853-9, Session 2

Integration of AdaptiSPECT: a small-animal adaptive SPECT imaging system

Cecile Chaix, Stephen Kovalsky, Matthew Kosmider, The Univ. of Arizona (United States); Harrison H. Barrett, Lars R. Furenlid, College of Optical Sciences, The Univ. of Arizona (United States)

No Abstract Available

8853-10, Session 3

Laser pixelation of thick scintillation detectors for medical imaging applications *(Invited Paper)*

Hamid Sabet, Haris Kudrolli, Zsolt Marton, Bipin K. Singh, Vivek V. Nagarkar, Radiation Monitoring Devices, Inc. (United States)

No Abstract Available

8853-11, Session 3

The effect of gain variation in micro-channel plates on gamma-ray energy resolution

Ling Han, The Univ. of Arizona (United States); Harrison H. Barrett, College of Optical Sciences, The Univ. of Arizona (United States); H. Bradford Barber, The Univ. of Arizona (United States); Lars R. Furenlid, College of Optical Sciences, The Univ. of Arizona (United States)

No Abstract Available

8853-12, Session 3

Development of plasma-display-panel-based x-ray detector (PXD)

Hakjae Lee, Kisung Lee, Korea Univ. (Korea, Republic of); Sangheum Eom, Hanho Park, Jungwon Kang, Dankook Univ. (Korea, Republic of)

No Abstract Available

8853-13, Session 3

Gamma-ray imaging studies of CsI(Tl) crystalline microcolumnar scintillators

H. Bradford Barber, The Univ. of Arizona (United States); Harish B. Bhandari, Radiation Monitoring Devices, Inc. (United States); Christopher Dumas, David Fastje, The Univ. of Arizona (United States); Haris Kudrolli, Vivek V. Nagarkar, Radiation Monitoring Devices, Inc. (United States)

No Abstract Available

8853-14, Session 3

The importance of image quality in medical imaging

Hans N. Roehrig, The Univ. of Arizona (United States)

No Abstract Available

8853-20, Session 3

Accurate system modeling of positron emission mammography

Bing Bai, The Univ. of Southern California (United States); Weidong Luo, Naviscan, Inc. (United States); Magnus Dahlbom, Univ. of California, Los Angeles (United States)

Objectives

A high-resolution positron emission mammography (PEM) scanner has been developed using two stationary panel detector heads. Due to its unique geometry, the point spread function (PSF) of the system is highly non-uniform. It has been shown from other PET systems that iterative reconstruction techniques using accurate system modeling are able to significantly improve image quality. Our aim of this study is to develop accurate system model of the PEM scanner with fast implementation for clinical PEM scans.

Methods

The Naviscan PEM scanner has been described previously [1]. We use GATE to simulate the system. A low activity point source is positioned inside the field of view (FOV). The source is moved on a grid to measure the PSF at different locations. Due to the symmetry of the scanner, the point source only needs to cover 1/8 of the FOV. A parametric model will be developed for fast implementation, similar to those used in PET scanners [2].

Results

GATE simulation results show that the PSF varies dramatically as the point source is moved across the FOV. The attached figure shows the distribution of counts of LORs in coincidence with a fixed crystal on the opposite panel. The top figure has the point source at the center of FOV, while for the bottom figure the source is moved 9mm toward one panel.

Conclusions

Simulated PSF of PEM scanner shows large variations, which need to be taken into account in reconstruction. We will develop fast implementations of accurate system model based on the GATE simulation. Results will be presented at the conference.

References:

1. W. Luo, E. Anashkin and C. G. Matthews, Performance Evaluation of a PEM Scanner Using the NEMA NU 4—2008 Small Animal PET Standards, IEEE Trans. Nucl. Sci., 2010

2. V. Y. Panin, F. Kehren, C. Michel and M. Casey, Fully 3-D PET reconstruction with system matrix derived from point source measurements, IEEE Trans. Med. Imag., 2006

8853-15, Session 4

Applying high frame-rate digital radiography and dual-energy distributed-sources for advanced tomosynthesis *(Invited Paper)*

Gil Travish, Univ. of California, Los Angeles (United States); Felix J. Rangel, Mark A. Evans, Kristin Schmiedehausen M.D., Radius Diagnostics Research, Inc. (United States)

Conventional radiography uses a single point x-ray source with a fan or cone beam to visualize various areas of the human body. An imager records the transmitted photons—historically film and now increasingly digital radiography (DR) flat panel detectors—followed by optional image post-processing. Tomosynthesis adds the ability to recreate quasi-3D images from a series of 2D projections. These exposures are typically taken along an arc or other path; and, tomosynthesis reconstruction is used to form a three-dimensional representation of the area of interest. Dual energy (two color) radiography adds the ability to enhance or “eliminate” structures based on their different attenuation of well-separated end-point energies in two exposures. These advanced capabilities come at a high cost in terms of complexity, imaging time, capital equipment, space, and potentially reduced image quality due to motion blur.

Recently, the prospect of creating x-ray sources, which are composed of arrays of micro-emitters has been put forward. These arrays offer a flat-panel geometry and may afford advantages in fabrication methodology, size and cost. They also facilitate the use of the dual energy technology. Here we examine the possibility of using such an array of x-ray sources combined with high frame-rate (~kHz) DR detectors to produce advanced medical images without the need for moving gantries or other complex motion systems. Combining the advantages of dual energy imaging with the ability to determine the relative depth location of anatomical structures or pathological findings from imaging procedures that are nearly identical to general radiology, should prove to be a powerful diagnostic tool. In addition to the requirements for the desired detector, we will present simulation results and use cases that would benefit from the capabilities of this modality.

8853-16, Session 4

A new apparatus of infrared videopupillography for monitoring pupil size

Mei-Lan Ko, National Taiwan Univ. Hospital, Hsin-Chu Branch (Taiwan); Ting-Wei Huang, Kuan-Heng Tao, Sing-Tsung Li, Yu-Chieh Huang, Wei-De Jeng, National Chiao Tung Univ. (Taiwan); Yu-Ta Chen, Yao-Fang Hsieh, National Central Univ. (Taiwan); Mang Ou-Yang, National Chiao Tung Univ. (Taiwan); Jin-Chern Chiou, National Chiao Tung Univ. (Taiwan) and China Medical Univ. (Taiwan)

People usually neglect the symptoms of glaucoma because they are not usually very obvious. We diagnosed or tracked glaucoma by the intraocular pressure (IOP) generally because IOP is one of the physiology parameters that are associated with glaucoma. This paper propose a platform to study the correlation between glaucoma and the physiology parameter, the pupil size. A device is instrumented to monitor the pupil size in an attempt to bypass the direct IOP measurement. The portable pupil metering device of first generation contains a camera, a beam splitter, the visible-light LEDs for stimulating the eyes, and the infrared LEDs for lighting the eyes. It can be modulated to focus on different eye locations, and can be mounted on an eyeglass frame. Computations correlate eye shapes with pupil size changes. Some drawbacks of first generation device are the large volume, heavy weight, some LED light spot, and less modulating dimensions for the camera focusing. Therefore, the portable pupil metering device of second generation are designed as a smaller and lighter device with more modulating dimensions, and will seek the approach to solve the LED light spots, just like the diffusor. We hope the measurement resulted with the pupil meter proposed in this paper can help measure the pupil contraction and correlate with different eye diseases in future.

8853-17, Session 4

Color in medical imaging

Hans N. Roehrig, The Univ. of Arizona (United States)

No Abstract Available

8853-18, Session 4

Efficient image acquisition design for a cancer detection system

Dung C. Nguyen, MIAO IC Design, LLC (United States); Janet M. Roveda, MIAO IC Design, LLC (United States) and The Univ. of Arizona (United States); Marisa H. Borders M.D., Kimberly A. Fitzpatrick M.D., Hans N. Roehrig, The Univ. of Arizona (United States)

Modern imaging modalities, such as Computed Tomography (CT), Digital Breast Tomosynthesis (DBT) or Magnetic Resonance Tomography (MRT) are able to acquire volumetric images with an isotropic resolution in micrometer (um) or millimeter (mm) range. When used in interactive telemedicine applications, these raw images need a huge storage unit, thereby necessitating the use of high bandwidth data communication link. To reduce the cost of transmission and enable archiving, especially for medical applications, image compression is performed. Recent advances in compression algorithms have resulted in a vast array of data compression techniques, but because of the characteristics of these images, there are challenges to overcome to transmit these images efficiently. In addition, the recently studies raise the low dose mammography risk on high risk patient. Our preliminary studies indicate that by bring the compression before the analog-to-digital conversion (ADC) stage is more efficient than other compression techniques after the ADC. The linearity characteristic of the compressed sensing and ability to perform the digital signal processing (DSP) during data conversion open up a new area of research regarding the roles of sparsity in medical image registration, medical image analysis (for example, automatic image processing algorithm to efficiently extract the relevant information for the clinician), further X-ray dose reduction for mammography, and contrast enhancement.

8854-1, Session 1

Dual gamma/neutron directional elpasolite detector *(Invited Paper)*

Paul P. Guss, Sanjoy Mukhopadhyay, National Security Technologies, LLC (United States)

Some applications, particularly in homeland security, require detection of both neutron and gamma radiation; this is accomplished by combining two detectors registering neutrons and gammas separately. We have investigated a new type of neutron/gamma (n/g) directional detection capability. We explored a new class of scintillator, Ce-doped Elpasolites such as Cs2LiYCl6:Ce (CLYC), Cs2LiLaCl6:Ce (CLLC), Cs2LiLaBr6:Ce (CLLB), and Cs2LiYBr6:Ce (CLYB). These materials provide energy resolution as good as 2.9% at 662 keV (FWHM), which is better than that of NaI:Tl. Because they contain 6Li, Elpasolites can also detect thermal neutrons. In the energy spectra, the full energy thermal neutron peak appears near or above 3 GEEn MeV. Thus, very effective pulse height discrimination is possible. In addition, the core-to-valence luminescence (CVL) provides Elpasolites with different temporal responses under gamma and neutron excitation, and, therefore, may be exploited for effective pulse shape discrimination. For instance, the CLLC emission consists of two main components: (1) CVL spanning from 220 to 320 nm and (2) Ce emission found in the range of 350 to 500 nm. The former emission is of particular interest because it appears only under gamma excitation. It is also very fast, decaying with a 2 ns time constant. The n/g discrimination capability of Elpasolite detectors may be optimized by tuning the cerium doping content for maximum effect on n/g pulse shape differences. The resulting Elpasolite detectors have the ability to collect neutron and gamma data simultaneously, with excellent discrimination. Further, an array of four of these Elpasolite detectors will perform directional detection in both the neutron and gamma channels simultaneously.

8854-2, Session 1

High-resolution Lu2O3:Eu scintillator for hard x-ray microtomography

Zsolt Marton, Harish B. Bhandari, Charlie Brecher, Stuart R. Miller, Bipin K. Singh, Vivek V. Nagarkar, Radiation Monitoring Devices, Inc. (United States)

No Abstract Available

8854-3, Session 1

An MAPMT-based test stand for rapidly assessing imaging performance of novel scintillators

Christopher Dumas, H. Bradford Barber, David Fastje, The Univ. of Arizona (United States); Joshua P. Tower, Kanai S. Shah, Radiation Monitoring Devices, Inc. (United States)

No Abstract Available

8854-4, Session 1

Ca2+-doped CeBr3 scintillating materials

Paul P. Guss, National Security Technologies, LLC (United States); Michael E. Foster, Bryan M. Wong, F. Patrick Doty, Sandia National Labs. (United States); Kanai S. Shah, Michael R. Squillante, Urmila Shirwadkar, Rastgo H. Hawrami, Josh P. Tower, Radiation Monitoring Devices, Inc. (United States); Ding Yuan, National Security Technologies, LLC (United States)

Despite the outstanding scintillation performance characteristics of cerium tribromide (CeBr3) and cerium-activated lanthanum tribromide (LaBr3:Ce), their commercial availability and application are limited due to the difficulties of growing large, crack-free single crystals from these fragile materials. Aliovalent doping was employed to strengthen CeBr3 in an effort to ease crystal growth constraints and improve ingot yields. One divalent dopant (Ca2+) was investigated to determine if it could strengthen CeBr3 without negatively impacting scintillation performance. Ingots containing nominal concentrations of 1.9% of the Ca2+ dopant were grown. Preliminary scintillation measurements are presented for this aliovalently doped scintillator. Ca2+-doped CeBr3 exhibited little or no change in the peak fluorescence emission for 371 nm excitation for CeBr3. The structural, electronic, and optical properties of CeBr3 crystals were investigated using the density functional theory within generalized gradient approximation. The calculated lattice parameters are in good agreement with the experimental data. The energy band structures and density of states were obtained. The optical properties of CeBr3, including the dielectric function, were calculated.

8854-5, Session 2

RIF neutron measurements through activation measurements *(Invited Paper)*

C. Bhatia, Duke Univ. (United States); Melissa Boswell, Malcolm Fowler, Los Alamos National Lab. (United States); M. Gooding, Duke Univ. (United States); Gary P. Grim, Andi Klein, A. Tonchev, Los Alamos National Lab. (United States); Werner Tornow, Duke Univ. (United States); B. Runderberg, Carl H. Wilde, Jerry Wilhelmy, Los Alamos National Lab. (United States)

No Abstract Available

8854-6, Session 2

Real-time active cosmic neutron background reduction methods *(Invited Paper)*

Sanjoy Mukhopadhyay, Paul P. Guss, Richard J. Maurer, Ronald S. Wolff, Stephen E. Mitchell, National Security Technologies, LLC (United States)

Neutron counting using large arrays of proportional counters from an aerial system or in a maritime environment suffers from the background counts from the primary cosmic neutrons and secondary neutrons caused by cosmic ray?induced mechanisms such as spallation and charge-exchange reaction. We have attempted two different methods to reduce the cosmic neutron background in real time. As a first step, both methods utilized shielding materials with high concentrations (up to 30% by weight) of neutron-absorbing elements, such as natural boron, to remove the low-energy neutron flux from cosmic neutrons. The goals of the first method were to design, prototype, and test an up-looking plastic scintillator to tag the cosmic neutrons and then create a logic pulse of a fixed time duration (~120 micro-s) to block the data taken by the neutron

counter (pressurized 3He tubes). The second method examined the time correlation between the arrival of two successive neutron signals to the counting array and calculated the excess of variance (Feynman variance) in the neutron count distribution from Poisson distribution. The dilution of this variance from cosmic background values ideally would signal the presence of man-made neutrons. The first method was successful in tagging the neutrons in the cosmic ray flux and preventing them from being counted in the 3He tube array by electronic veto. The second method has successfully derived an empirical relationship between the percentile non-cosmic component in a neutron flux and the Feynman variance Y2F of the measured neutron count distribution.

8854-7, Session 2

Preparing for the 100-megapixel detector: reconstructing a multi-terabyte computed-tomography dataset

Laurel J. Orr, Edward S. Jimenez, Sandia National Labs. (United States)

Although there has been much progress in applying GPU-technology to Computed-Tomography reconstruction algorithms, much of the work has concentrated on optimizing reconstruction performance for smaller medical-scale datasets. Industrial CT datasets can vary widely in size and number of projections. With the new advancements in high resolution cameras, it is entirely possible that the Industrial CT community may soon have the need to pursue a 100-megapixel (10Kx10K pixels) detector for CT applications. Simply adding extra GPUs would not be an option as memory and storage bottlenecks would result in prolonged periods of GPU downtime. Additionally, current reconstruction algorithms (CPU and GPU-based) would not be sufficient due to the various bottlenecks in the processor hardware. Past work has shown that CT reconstruction is an irregular problem on a GPU due to the massively parallel environment. This work proposes a high-performance multi-GPU modularized approach to reconstruction such that computation, memory transfers, and disk I/O can occur in parallel while accommodating the irregular nature of the computation kernel. Our approach utilizes a dynamic MIMD-type of architecture in a hybrid environment of CUDA and Open-MP. The modularized approach showed an improvement in load-balancing and performance such that a 1 trillion voxel volume was reconstructed from 10K 100-Megapixel projections in less than a day.
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energys National Nuclear Security Adminis- tration under contract DEAC04-94AL85000.

8854-8, Session 2

Rethinking the union of computed tomography reconstruction and GPGPU computing for industrial applications

Edward S. Jimenez Jr., Laurel J. Orr, Sandia National Labs. (United States)

No Abstract Available

8854-9, Session 3

High-rate beta decay measurement at Omega and NIF *(Invited Paper)*

Andi Klein, Robert Aragonez, Melissa Boswell, Malcolm Fowler, Jeffrey R. Griego, Gary P. Grim, Robert Rundberg, Carl H. Wilde, Jeremy Wilhelmy, Los Alamos National Lab. (United States)

One of the most challenging problems in high-energy-density physics is the calculation of turbulent mixing in compressible and converging flows with thermonuclear (TN) energy release. This mixing originates from hydrodynamical instabilities at material interfaces, which are created by laser driven ablation and compression of D-T capsules at Omega and NIF. To study the underlying physics, the shell gets doped with different material, which will be activated through either the 14 MeV neutrons of charged particles. We have developed a detector system, which is capable to measure energy and decay time of the resulting Beta Decay, in a high rate environment. We are using a segmented scintillator telescope, which has an energy resolution of 400 keV and can handle rates up to 4 MHz. Th signals from the PMTs are recorded by 4 channel digitizer scopes and a fast 8 channel digitizer card. We will also present results on a new digitizer prototype with higher throughput.

8854-10, Session 3

Combining signals from multiple-coded apertures for source reconstruction from low signal-to-noise ratio images

Nevzat Guler, Christopher R. Danly, Gary P. Grim, Frank E. Merrill, Petr L. Volegov, Carl H. Wilde, Los Alamos National Lab. (United States)

No Abstract Available

8854-11, Session 3

Techniques for co-registered neutron and x-ray imaging of ICF experiments

Christopher R. Danly, Gary P. Grim, Frank E. Merrill, Carl H. Wilde, Petr L. Volegov, Nevzat Guler, Miranda Intrator, Los Alamos National Lab. (United States)

No Abstract Available

8854-12, Session 3

Testing of the Gamma Ray Diagnostic System at Los Alamos Microtron and Omega Laser

Daniel Lemieux, College of Optical Sciences, The Univ. of Arizona (United States)

Abstract: The National Ignition Facility at Lawrence Livermore National Laboratories has had a need for a Gamma Ray Diagnostic System to analyze the ablator symmetry. Ongoing work at the University of Arizona and Los Alamos has resulted in a prototype imaging system. This system has been tested using a Bremsstrahlung Microtron source at Los Alamos National Laboratory. This test demonstrates the proof of concept of the systems ability to image MeV gammas. Further work on characterizing the system will take place at the Omega Laser at the University of Rochester by way of hard x-rays.

8854-13, Session 3

Correlation of neutron imaging and time-of-flight data at the National Ignition Facility

Gary P. Grim, Christopher R. Danly, Los Alamos National Lab. (United States); David N. Fittinghoff, Lawrence Livermore National Lab. (United States); Nevzat Guler, Frank E. Merrill, George L. Morgan, Carl H. Wilde, Douglas C. Wilson, Los Alamos National Lab. (United States)

No Abstract Available

8854-14, Session 4

Penetrating radiation applications at Los Alamos National Laboratory *(Invited Paper)*

Scott Watson, Samuel Gonzales, Gwynneth A. Cunningham, Los Alamos National Lab. (United States)

No Abstract Available

8854-15, Session 4

Dual view x-ray inspection system based on FPGA technique *(Invited Paper)*

Zhiwen Lu, Ning Song Peng, Shanghai Gaojing Metal Detector Instrument Co., Ltd. (China)

X-ray inspection technique for foreign objects in food products can determine the presence of contaminants within the product and reject by using image process and pattern recognition technique on the X-ray transmission images. This paper presents dual view X-ray inspection system based on FPGA technique for foreign objects in food jar via analyzing the weak point of the traditional single view X-ray inspection technique. In addition, a prototype with the new technique is developed in accordance with glass splinters detection and rejection within the food jar (glass jar especially) which is a typical tickler. This paper describes the rejection control system based on FPGA technique and the concrete realization method, with which, the prototype can detect the NG(not good) jars with 3mm diameter foreign splinter and continuously reject them accurately at the speed of 40m/min. This system effectively reduces the mistake rate and miss rate for food products checking, and greatly improves the production efficiency simultaneously. Finally the actual test results of this prototype are given.

Key words: FPGA technique; dual view X-ray; X-ray machine; X-ray Inspection technique

8854-16, Session 4

Non-linear response of image intensifiers: consequences for gamma-ray imaging

David Fastje, Ling Han, H. Bradford Barber, The Univ. of Arizona (United States)

No Abstract Available

8854-17, Session 4

Imaging properties of pixelated scintillators with deep pixels

H. Bradford Barber, David Fastje, The Univ. of Arizona (United States)

No Abstract Available

8855-300,

Trends and Challenges in Open Source Software

Stephen Aylward, Kitware, Inc. (United States)

Over the past decade, the field of medical image analysis research has undergone a rapid evolution. It was a collection of disconnected efforts that were burdened by mundane coding and file I/O tasks. It is now a collaborative community that has embraced open-source software as a shared foundation, reducing mundane coding and I/O burdens, promoting replicable research, and accelerating the pace of research and product development. This talk will review the history and current state of open-source software in medical image analysis research, will discuss the role of intellectual property in research, and will present emerging trends and technologies relevant to the growing importance of open-source software.

8855-1, Session 1

Production, detection, and manipulation of scalar vortex and radially polarized beams *(Invited Paper)*

Ignacio Moreno, Univ. Miguel Hernández de Elche (Spain)

In this work we will describe techniques for the generation of vortex beams, including vortex generating diffraction gratings and diffractive lenses, as well as some possible applications in optical image processing. We will then analyze the description of radially polarized beams in terms of superposition of such vortex beams. We will present some methods for the production of radially polarized light, that include patterned linear polarizers, specially designed liquid crystal devices and spatial light modulators (SLMs). We will analyze the manipulation of this radial polarization by means of wave-plates, in order to obtain other non-standard spatially variant polarized light beams. Theoretical analysis will be presented based on the Jones matrix theory, and experimental results will be included for all cases.

8855-2, Session 1

Optical asymmetric cryptosystem using polarized light

Sudheesh K. Rajput, Naveen K. Nishchal, Indian Institute of Technology Patna (India)

We propose an optical asymmetric image encryption scheme using phase-truncated Fourier transform and polarization encoding. An image bonded with a random phase mask is Fourier transformed and then the spectrum is amplitude- and phase- truncated. The phase-truncated value is encrypted using the concept of polarized light in which two independent optical plane waves are used. The first plane wave illuminates input image and is encoded into a given state of polarization. The second plane wave illuminates an intensity key image and is encoded into another state of polarization. Thus obtained two waves are mixed to obtain first level of encryption. The resultant is then passed through a matrix of linear polarizer (pixilated polarizer), to obtain second level of encryption. For decryption, the encrypted image is passed through the same pixilated polarizer at exact angles. Finally, the decrypted image is obtained by computing Fourier transform of the retrieved phase-truncated value bonded with amplitude-truncated value.

The proposed method offers flexibility in the encryption key design. Due to amplitude- and phase- truncation process the designed keys are asymmetric in nature. We also checked the immunity against special attack if polarization keys are unknown. Results of numerical simulation are presented in support of the proposed scheme.

8855-3, Session 1

Study of the modulation capabilities of parallel aligned liquid crystal on silicon displays

Andrés Márquez, Univ. de Alicante (Spain); Francisco J. Martinez-Verdu, Univ. de Alicante (Spain); Sergi Gallego, Manuel Ortuño, Jorge Francés Monllor, Augusto Beléndez, Inmaculada Pascual, Univ. de Alicante (Spain)

Among the existent technologies of spatial light modulator devices, parallel aligned liquid crystal on silicon displays (PA-LCoS) have found wide acceptance. They are especially interesting since they provide phase-only modulation with no coupling of amplitude modulation. Optimal use of these devices requires proper calibration of their modulation capabilities in order to minimize some degradation effects found in the literature, such as flicker or anamorphic and frequency dependent modulation. In this work we apply calibration techniques developed in our lab, basically the classical linear polarimeter adapted to be able to take into account the existence of flicker. This method enables to obtain both the average retardance and a good estimation of the magnitude of the phase fluctuation when flicker is present. Various addressing formats are considered together with variations in the magnitude of the applied voltages in order to amplify the retardance dynamic range and to enhance linearity in the device. Finally some applications in diffractive optics will be given.

8855-4, Session 1

Cardiac rate detection method based on the beam splitter prism

Lei Yang, Xiaohua Liu, Ming Liu, Yuejin Zhao, Liquan Dong, Ruirui Zhao, Xiaoli Jin, Beijing Institute of Technology (China)

A new cardiac rate measurement method is proposed. Through the beam splitter prism, the common optical system of the transmitting and receiving signals is achieved. By the focusing effect of the lens, the small amplitude motion artifact is inhibited and the signal-to-noise is improved. The cardiac rate is obtained based on the PhotoPlethysmoGraphy (PPG). We use the LED as the light source and use the photoelectric diode as the receiving tube. The LED and the photoelectric diode are on the different sides of the beam splitter prism and they form the optical system. The signal processing and display unit is composed by the signal processing circuit, data acquisition device and computer. The light emitted by the modulated LED is collimated by the lens and irradiate the measurement target through the beam splitter prism. The light reflected by the target is focused on the receiving tube through the beam splitter prism and another lens. The signal received by the photoelectric diode is processed by the analog circuit and obtained by the data acquisition device. Through the filtering and Fast Fourier Transform, the cardiac rate is achieved. We get the real time cardiac rate by the moving average method. We experiment with 30 volunteers, containing different genders and different ages. We compare the signals captured by this method to a conventional PPG signal captured concurrently from a finger. The results of the experiments are all relatively agreeable and the difference is about 2bmp.

8855-5, Session 2

Digital holographic tomography using a light back propagation method and its application for refractive index measurement

Takanori Nomura, Takahiro Kitazawa, Wakayama Univ. (Japan)

Digital holography is one of the two-dimensional measurement methods for refractive index distribution. Refractive index distribution is obtained from phase distribution measured by digital holography.

In digital holographic tomography, which combines digital holography and filtered back projection method, it enables to measure three-dimensional distribution of refractive index. However, a filtered back projection method requires a little phase delay of a measured specimen. The amount of phase delay should be so small that the effect of the refraction is negligible. Therefore, digital holographic tomography using filtered back projection method is used as an imaging digital holography. It can only measure small objects such as pollen cells with a diameter of 30 micrometer. In this paper, a lensless digital holographic tomography using not a filtered back propagation method but a light back propagation method is proposed. In the proposed method, the light propagates along a refracted optical path because the phase distribution of the detector. Therefore the deflection from a true optical path is reduced. For the measurement of specimen with a huge refraction angle, our proposed method improves on measurement accuracy compared with a conventional filtered back projection method. Both numerical simulations and optical experiments are given to confirm the feasibility of the proposed method.

8855-6, Session 2

Designing the acousto-optical cell for optical spectrometer incorporated into the Guillermo Haro astrophysical observatory

Alexandre S. Shcherbakov, Adan O. Arellanes, Vahram Chavushyan, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Optical spectrometer of the Guillermo Haro astrophysical observatory (Mexico) exploits mechanically removable diffraction gratings as dispersive elements. This spectrometer uses the gratings having 50 – 600 lines/mm with the optical apertures 9 x 9 cm that provide the first order spectral resolution from 9.6 to 0.8 A/pixel, respectively, in the range 400 – 1000 nm. However, the needed mechanical manipulations, namely, replacing the diffraction gratings with various resolutions and following recalibration of spectrometer within studying even the same object are inconvenient and lead to loosing rather expensive time for observation. We suggest exploiting an acousto-optical cell as a dispersive element in that spectrometer. Potentially, involving acousto-optical technique, which can realize tuning both the spectral resolution and the range of observation electronically, makes possible eliminating the above-mentioned demerits. The requirements to the cell combine a large optical aperture with the needed stroke-density and possibly high efficiency of operation under an acceptable acoustic power. This is why initially we consider the stroke-density 300 lines/mm. The analysis shows that at least the following materials can be used for designing similar cell. It can be lithium niobate ($LiNbO_3$)-crystal excited by the longitudinal acoustic mode along the [100]-axis at the frequency 2 GHz. This selection gives 300 lines/mm with total losses ~5.4 dB/aperture. Then, one can consider bismuth germanate ($Bi_{12}GeO_{20}$)-crystal using the shear acoustic mode along the [110]-axis at 0.53 GHz, so that the density 300 lines/mm appears with the losses ~6.3 dB/aperture. The neighboring figures of acousto-optical merit for these materials promise desirable efficiencies of operation, acceptable for astrophysical observations.

8855-7, Session 2

Fast hologram pattern generation by wave field translation

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Holographic display is considered as ideal 3D display because it can generate whole 3D information of light distribution which can be seen in any direction without visual discomfort. Computer generated hologram (CGH) can be made from discrete input signal such as color plus depth data. In previous work of authors, radial symmetric interpolation (RSI) method which exploits concentric redundancy of point hologram was proposed. In this approach, pattern generation complexity is reduced by substituting calculation of wave equation by copy operation using elemental fringe LUT. However, the performance of point source based method is limited by accumulation complexity. Every point hologram for each object point should be accumulated to obtain final hologram pattern, and as input point number increases, this accumulation complexity becomes dominant compared to pattern calculation complexity. In this paper, we present a 2 step hologram pattern generation method to overcome this accumulation problem of point source based method. Proposed method consists of two steps. In the first step, 2D projection of wave field for 3D object is calculated by RSI method to the predefined reference depth. Then in the second step, 2D wave field which is obtained from first step is translated toward depth direction and hologram pattern in SLM plane is calculated by FFT based algorithm on the Fresnel or Fraunhofer approximation. The effectiveness of method is proved by computer simulation and optical experiment. Experimental results show that proposed method is 3878 times faster than analytic method, and 226.4 times faster than RSI method.

8855-8, Session 2

Improvement of off-axis holographic storage with multi-layer recording medium

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There are many applications of holography, such as three-dimensional image, holographic optical testing, holographic optical element, holographic data storage, etc. The holographic data storage is superior to traditional optical data storage for high transfer rate and high capacity. In general, the recording medium of holographic data storage is single layer. In order to get larger storage capacity, the medium is supposed to be thicker. However, it makes the storage system sensitive to thermal expansion. In this paper, we propose a multi-layer recording medium in the off-axis holographic data storage that improves the thermal tolerance and maintains the shifting selectivity simultaneously. We derive the diffraction formula with thermal expansion based on the VOHIL theory, and then simulate the performance of the single layer recording medium of the system, including shifting selectivity and thermal tolerance. Finally we analyze the shifting selectivity and the thermal tolerance with different arrangement of the multi-layer recording medium.

8855-9, Session 2

Storage density estimation for the phase-encoding and shift multiplexing holographic optical correlator

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Optical holographic data storage has been a vibrant area of research

[1]. The object and reference beams interfere inside volume holographic memories, e. g. a LiNbO3 crystal, and the stationary interference patterns are formed inside the recording medium by the refractive index modulation [2]. Thousands of the data pages can be stored inside one single location in the crystal through angular, phase-encoded, wavelength, or by more than one of these techniques in combination [3]. The high performance volume holographic correlator is based on the high-density holographic storage and has potential applications in associative retrieval, pattern recognition, target tracking, among others [4].

As the volume information density (VID) is crucial for a storage system, the VID needs to be estimated precisely. The VID follows VID=DA/V, where DA is the amount of data stored and V is the corresponding storage volume where the holograms are recorded. However, V is always estimated by the meeting volume formed by the object beam and reference beam in the traditional method. When multiple locations of a same crystal are applied for data storage, the estimation of V with the method mentioned is not precise. The value of V could be more credible if determined by the experiment. In this manuscript, we propose a system with a precise 2D translation stage for positioning the crystal. With this system, the minimum storing volume for one location is estimated precisely by translating the crystal until the stored data in one location of the crystal cannot be detected. So the optical holographic storage density is estimated with a high accuracy.

A hybrid shift multiplexing method for an off-axis optical holographic storage is proposed. When storing pages of data into different locations in the crystal, multiple phase masks are applied into the object beams. Each phase mask corresponds to one location. Compared with the non-phase-mask method, the minimum storing volume for one storage location is reduced, due to the selectivity introduced by different masks. The VID is enhanced with the phase mask method. The optical storage density of the storage system, with phase mask, is estimated with a translation stage in the experiments. The estimated density is more accurate than with the traditional method and the density rises with the phase-encoded multiplexing method. It enables the optical storage system for the applications as high speed computation.

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8855-27, Session PWed

Integration of coherent optical OFDM with WDM

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Orthogonal Frequency Division Multiplexing (OFDM) got a great attention in optical communications due to its ability to overcome different limitations in optical fiber such as polarization mode dispersion and chromatic dispersion. Coherent optical OFDM (CO-OFDM) combines the attractive advantages of both OFDM and coherent detection. CO-OFDM has proved to be an efficient technique that can be used in high speed optical transmission and to enhance the data to exceed 100 Gbits/s due to its high spectral efficiency and ability to overcome fiber dispersion. WDM (Wavelength division multiplexing) is an optical technique used to extend the bandwidth and support high data rate where many signals can be combined and transmitted at the same time. This paper proposes a system design that integrates CO-OFDM with WDM to reach data rate of 400 Gbits/s over 1000 Km Single Mode Fiber (SMF). The 400 Gbits/s signal is generated by multiplexing eight OFDM with 50 Gbits/s for each OFDM. Two different scenarios are studied and compared to analyze the performance of the system to find out how the dispersion and the nonlinearities affect the system. The first scenario is to study the performance of CO- OFDM WDM back to back design by measuring the BER and the OSNR (Optical Signal to Noise Ratio) of different WDM channels and studying the constellation diagram of each user. The second scenario is to study the performance of CO-OFDM WDM for 1000 Km SMF by measuring the BER and the OSNR of different WDM channels and studying the constellation diagram of each user.

8855-28, Session PWed

Theoretical and experimental examination of PQ-PMMA photopolymer material

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Phenanthrenequinone (PQ) doped poly(methyl methacrylate) (PMMA) photopolymer material has been studied extensively due to the growing interest in application involving photopolymers. However, to progress the development a more physical material model has become necessary. In this article, a kinetic model is developed, which includes: (i) the time varying photon absorption, including the absorptivity of a second absorber, i.e., the singlet excited state of PQ, (ii) the recovery/regeneration and the bleaching of the excited state PQ, (iii) the nonlocal effect, and (iv) the diffusion effects of both the ground and excited state PQ molecules and of the methyl methacrylate (MMA). A set of rate equations are derived, governing the temporal and spatial variations of each chemical component concentration. The validity of the proposed model is examined by applying it to fit experimental data for PQ-PMMA layers containing three different initial PQ concentrations, i.e., 1 mol.%, 2 mol.% and 3 mol.%. The effect of different exposure intensities is also examined. Material parameters are extracted by numerically fitting experimentally measure normalized transmission curves and the refractive index modulation growth curve using the theoretical models.

8855-29, Session PWed

Spatial frequency response of AA/PVA photopolymer material containing four different photosensitizers

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Based on the previous study of the time varying photon absorption effects, the behaviour of four different photosensitizers in an AA/PVA photopolymer material has been further examined by using the developed 1-D Nonlocal Photo-polymerization Driven Diffusion (NPDD) model. In order to characterise the photosensitizers precisely, holographic illuminations with different spatial frequencies are applied. Material parameters, i.e., the nonlocal response parameter, ?, the diffusion rate of monomer, Dm, the chain initiation kinetic constant, ki, and the termination rate, kt, are extracted by numerically fitting experimentally measure the refractive index modulation growth curve using the theoretical models. In this paper, the four different photosensitizers under investigation are Erythrosin B; Eosin Y; Phloxine B; Rose Bengal.

8855-30, Session PWed

Anaglyph stereo images generated from objects topography obtained by projection fringes

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The structured light techniques are useful to evaluate the topography of an object. A grid of straight lines is projected onto the surface of a diffusely reflective object. By using the Fourier transform the phase of a fringe pattern is obtained from a single image. With the phase information and the sensibility vector of the optical system the value at each object´s point is determined. On the other hand, 3D visualization is possible by using a stereoscopic system that provides two different images of the same object (one for each eye). One possible technique is that known as the anaglyph method. This is based on the binocular disparity of two images obtained with different color filters. Each one of the images is taken with complementary colors (red-blue or red-green). The tri-dimensional shape is observed by the use of special glasses. In this form, every eye sees an image from its own angle. The object topography is obtained with the fringe projection technique and then one image is selected and pseudo colored. Then, the second image is taken by slightly changing the perspective of the tri-dimensional display and pseudo coloring it with a complimentary color. A computational algorithm is developed to evaluate and visualize the object in real time which uses the spectral absorption curves of the glasses, the spectral density functions of the display primaries and the colorimetric properties of the human observer. Experimental results are shown of the evaluation and visualization of a porcine vascular segment.

8855-32, Session PWed

Enhancement of nonlinear phase shift for format conversion in silicon waveguides

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Different modulation formats may be required in different optical communications networks. Differential phase-shifted keying (DPSK) format is competitive for long-haul transmission and on-off keying (OOK) format is suitable for metropolitan area networks. As a result, format conversion is needed from intensity format to phase format in edge nodes. Silicon waveguides based on silicon-on-insulator technique have attracted increasing attentions for nonlinear applications due to its strong third-order nonlinearity and large refractive index contrast. Cross-phase modulation (XPM) in silicon waveguides provides a promising way to realize all-optical integrated format conversion since a nonlinear phase shift is induced to the probe by the incident signal power. An OOK format can be converted to DPSK format if nonlinear phase shift of π is generated. In this paper, the nonlinear phase shift caused by XPM have been numerically investigated. The influences of the walk-off effect, group-velocity dispersion, and nonlinear losses (including two- photon absorption (TPA) and free-carrier absorption (FCA)) on the nonlinear phase shift have been analyzed in detail. We tried to enhance the nonlinear phase shift by cancelling these influences. We found that the walk-off effect can be minimized by carefully choosing the zero dispersion wavelength of the used silicon waveguide and the probe wavelength to make the signal and the probe symmetrically. Flat and small dispersion is beneficial to acquire a large nonlinear phase shift. TPA and FCA will greatly reduce the nonlinear phase shift obtained from XPM and they should be effectively suppressed in order to realize high-quality format conversion.

8855-33, Session PWed

Known plain-text attack on asymmetric cryptosystem

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It is believed that asymmetric cryptosystem based on phase-truncated Fourier transform has immunity against known-plaintext attack. However, generation of two asymmetric keys is possible, if plaintext-ciphertext pair is known. In this paper, we show that amplitude- and phase- truncation-based asymmetric cryptosystem is vulnerable to known-plaintext attack. The decryption keys are generated with the help of modified Gerchberg-Saxton phase retrieval algorithm from known-plaintext and cipher-text. The first key is generated from known-plaintext and the second key is generated from the cipher-text. With the help of the generated keys, the encrypted image in one domain is decrypted successfully in another domain. The domains used for this study are Fourier, Fresnel, or fractional Fourier domain. The vulnerability is proved through the results of computer simulation.

8855-34, Session PWed

Analysis of the fabrication of diffractive optical elements in photopolymers

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Recently the possibility to record phase diffractive optical elements (DOEs) onto photopolymers has been explored. The use of a spatial light modulator gives us the possibility to record a wide range of diffractive elements. Sharp profiles may as well present a smoothing of the edges due to various reasons: a low pass filtering of the optical system, material properties, etc. In this work we have analyzed the importance of some of these aspects of the photopolymer and the experimental set-up in order to record high quality DOEs. The photopolymer analyzed is based on polyvinylalcohol/acrylamide.

8855-35, Session PWed

Spatial attributes of the diffraction field

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Optical diffraction fields have in general a spatial complex structure and some times can generate focusing regions, in this work we describe the focusing region associated with highly symmetric transmittances, analyzing its associated phase function. We show that generic features can be studied from a differential equation for a focusing geometry, which is obtained through angular representation for diffraction fields, according to the choice of the parameters involved, the diffraction field presents a new focusing region whose geometry and spatial evolution can be described with the only analysis of the phase singularities avoiding the integral representation.

8855-36, Session PWed

An object boundary detection system based on a 3D stereo monitor

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Finding object boundary is one of the most challenging tasks in image processing, and it has important applications in many areas such as medical and biological imaging. Numerous image segmentation algorithms have been proposed to detect object boundary, among which active contours, level set methods and graph cut are widely used especially for medical images because of their good performance in segmentation. These algorithms are usually computational expensive due to many iterations needed and thus not suitable for real-time processing. Optical processing can be used for real-time object detection through utilizing parallel processing and implementing high-pass filters, but it is impractical due to coherent illumination needed and unsatisfied results. In this paper we propose a novel object boundary detection system based on a 3D stereo monitor. The image processing is based on controlling the polarization of LCD and the way the image is display on a 3D monitor to enhance object boundary. The users can see the enhanced contour of the object through a 3D polarization glasses in real-time, which can be also recorded using a camera for further processing. A software is developed for user interaction to achieve better results. The effectiveness of the system is demonstrated using various medical and biological images. It has the advantages of high speed processing and robustness to noise over the digital methods.

8855-10, Session 3

Implementation of a photonic antenna in optical OFDM link

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The integration of photonic antennas with radio over fiber (RoF) systems can serve high dense populated areas such as airports, shopping centers, dead-zone area and tunnels. In this paper, we present an optical wireless communication downlink with a photonic antenna. Our proposed radio over fiber (RoF) system is to carry modulated orthogonal frequency division multiplexing (OFDM) signals with a 2.4 GHz radio frequency over a cost effective optical link. A comparison of using the photonic antenna as a passive and an active in the RoF system is presented. The active photonic antenna (APHA) is mounted at the end of the optical link to the photodiode as a package of a band-pass filter (BPF) and a radio frequency power amplifier. The photonic antenna scattering parameters are implemented into the optical system simulation tools at various fiber length and free space loss (FSL). The wireless link is implemented for a transmission distance up to 100 meters. The transmitted signal is fully carried over a radio frequency signal and then optically carried over a standard single mode fiber (SSMF). The measurements of the EIPR and SNR were done with 0 dBm RF input into the directly modulated laser (DML) for all the simulations. The results show that the analog optical wireless link is very suitable to carry the OFDM signals. Moreover, the active photonic antenna provides sufficient service for more than 30 meters compared to passive antenna.

8855-11, Session 3

Optical signal impairment study of cascaded optical filters in 40 Gbps DQPSK and 100 Gbps PM-DQPSK systems

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The optical filter is a crucial element in optical communications. The influence of cascaded filters in the optical signal will affect the communications quality seriously. In this paper we will study and simulate the optical signal impairment caused by different kinds of filters which include Butterworth, Bessel, Fiber Bragg Grating (FBG) and Fabry-Perot (F-P). Optical signal impairment is analyzed from an Eye Opening Penalty (EOP) and optical spectrum point of view. The simulation results show that when the center frequency of all filters aligns with the laser's frequency, the Butterworth has the smallest influence to the signal while the F-P has the biggest. With an 1-dB EOP, the amount of cascaded Butterworth optical filters with a bandwidth of 50 GHz is 18 in 40 Gbps NRZ-DQPSK systems and 12 in 100 Gbps PM-NRZ-DQPSK systems. The value is reduced to 9 and 6 respectively for Febry-Perot optical filters. In the situation of frequency misalignment, the impairment caused by filters is more serious. Our research shows that with a frequency deviation of 5 GHz, only 12 and 9 Butterworth optical filters can be cascaded in 40 Gbps NRZ-DQPSK systems and 100 Gbps PM-NRZ-DQPSK systems respectively. We also study the signal impairment caused by different orders of the Butterworth filter model. Our study shows that although the higher-order has a smaller clipping effect in the transmission spectrum, it will introduce a more serious phase ripple which seriously affects the signal. Simulation result shows that the 2nd order Butterworth filter has the best performance.

8855-12, Session 3

PAPR mitigation algorithms for OFDM WiMAX link

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OFDM has been adopted in many high systems due to its high data rates and to its robust performance in fading channel. OFDM distributes the data among number of carriers which are called subcarriers. The subcarriers must be orthogonal to prevent the carrier from interfering to each other. Features such overcoming ISI (inter-symbol interference) and the complexity of Designing both receiver and transmitter made it ideal technique for both wired and wireless communication as long as optical communications. However, OFDM suffers from a defect called Peak Average power ratio (PAPR). APARP is crucial drawback that limits the way that OFDM functions and reducing or mitigating this factor in wireless and optical environment will help overcome and enhance the OFDM date rate. PAPR is the main cause of inter-carrier interference and high out-of-band power, and consequently Bit error rate BER. We investigate some of the techniques that mitigate the effect of PAPR. These techniques are merged together to provide a better PAPR reduction with the existing techniques. In this paper, we are proposing a new reduction algorithm to minimize the effect of the PAPR. The results and simulation are done in Optisystem V-11 and Matlab environment. These approaches will be applied on WiMAX application and the performances between the different techniques are examined.

8855-13, Session 3

Electro-optic logic circuits based on silicon microring switches

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Electro-optic logic is a paradigm which employs the optical switch network to perform the logical operation. The status of each switch in the optical network is determined by an electrical Boolean signal applied to it. The operation of each switch is independent of the operations of other switches in the network and the operation result propagates in the network at the speed of light. The overall latency of the logic circuit is very small and all switches perform their operations almost simultaneously. Therefore, the electro-optic logic has a very high operation speed [1-4]. Silicon microring resonator is an attractive structure owing to its outstanding performances, such as compact size, ultra-low power consumption and CMOS-compatible process. Therefore, the electro-optic logic based on silicon microring switches is easy to realize large-scale integration and low-cost manufacture in a high-volume CMOS-photonics foundry. In the past several years, we proposed and demonstrated a series of electro-optic logic circuits based on silicon microring switches including NOT, XOR/XNOR, OR/NOR, AND/NAND, encoder, decoder and half-adder [5-13]. In this paper, we will review our recent research on electro-optic logic circuits based on silicon microring switches and introduce our new development in this topic.

8855-14, Session 4

On-chip optical matrix-vector multiplier *(Invited Paper)*

Lin Yang, Lei Zhang, Ruiqiang Ji, Institute of Semiconductors (China)

Matrix-vector multiplication is a fundamental operation in modern digital signal processing fields. Inspired by the intrinsic spatial parallelism of optics, much effort has been made to develop optical apparatuses that can perform such a parallelizable operation. The Stanford multiplier [1] is one of the most notable demonstrations, which is composed of light source array, optical lens, spatial light modulator (SLM) matrix and photodetector array. Almost all implementations are large in volume and high in power consumption. Moreover, many removable elements adopted make them extremely sensitive to the environmental vibration. To overcome these limitations, we propose an on-chip optical matrix-vector multiplier (MVM), which is composed of laser-modulator array, multiplexer, splitter, microring modulator matrix and photodetector array. Compared with traditional implementations, the use of wavelength multiplexing simplifies the fan-out and fan-in sub-systems. And the use of high-speed, planar integrated, wavelength specific 2-D matrix simplifies the low-speed, bulk, monochromatic 3-D spatial light modulators. The fan-out and fan-in with optical lenses in the traditional optical MVMs are replaced by the power splitting and wavelength multiplexing with waveguide devices in the proposed optical MVM, which greatly reduces the complexity and size of the system. The discrete components in the traditional optical MVMs are replaced by the integrated ones in the proposed optical MVM, which improves the stability and power efficiency of the system. 8x107 multiplications and accumulations per second is implemented by a demo system with a 4x4 microring modulator matrix [2]. Theoretical maximum performance of the proposed architecture is analyzed based on current technological level.

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8855-15, Session 4

Highway traffic segmentation and classification using super-resolution and Gaussian mixture model

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Super-resolution (SR) refers to reconstructing a single high resolution (HR) image from a set of subsampled, blurred and noisy low resolution (LR) images. In many cases, the acquisition sensors such as the video cameras that monitor the highway traffic have very limited quality. The reconstructed image suffers from degradations such as blur, aliasing and photo-detector noise which results in poor performance of the segmentation and classification of high way traffic. Our goal is to identify and extract individual vehicles from a highway traffic scene in these low quality images under different weather conditions. In this paper, we introduce a new fast stochastic Wiener filter to enhance spatial details and reduce acquisition artifacts through SR reconstruction. Wiener filter can be used to remove artifacts and enhance the visual quality of the reconstructed images. Our derivation depends on the continuous-discrete-continuous (CDC) model that represents most of the degradations encountered during the image-gathering and image-display processes. In addition, we incorporate a new parameter that accounts for LR images registration and fusion errors. Also, we speeded up the performance of the filter by constraining it to work on small patches of the images. We subsequently utilize (GMM) method to extract individual vehicles in a frame. Individual vehicles are clustered and detected from the segmented scene through the use of a series of morphological operations, followed by two-dimensional connected component labeling. We evaluate our hybrid approach quantitatively and qualitatively in segmentation and classification of the extracted vehicles.

8855-16, Session 4

Object tracking under nonuniform illumination with adaptive correlation filtering

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A real-time system for illumination-invariant object tracking is proposed. The system is able to estimate at high-rate the position of a moving target in an input scene, that is affected by presence of a high cluttering background and nonuniform illumination conditions. The position of the target is estimated with the help of a filter bank implemented on a graphics processing unit, exploiting massive parallelism. The filters in the bank, adapt their parameters according to the local statistics of the observed scene, in a small region centered at coordinates of a predicted position for the target. As a result, we can reduce the size of the input frame to search for the target, and we can reduce the number of required filters in the bank to increase operation speed. The predicted position for the target is carried out by exploiting information of present and past frames, and by using the coordinated turn motion model of the target in a two-dimensional plane. Computer simulation results obtained with the proposed system are presented and discussed in terms of tracking accuracy, computational complexity, and tolerance to nonuniform illumination.

8855-17, Session 4

A novel discretization method with geometric symmetry for image reconstruction

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Pixel based discretization is currently applied in image reconstruction for computerized tomography(CT), but it does not take into account the geometry symmetry of scanning configuration. In this work, we propose a discretization method for the image reconstruction of CT. Based on the scanning configuration and image resolution under reconstruction, the Radon transform is discretized to minimize the sampling artifacts. In this discretization, the projection coefficient is weighted by the distance from the pixel to the ray rather than the intersection. So the sampling error by convolution is reduced. Further more, this discretization can lead to faster algorithms implementation because of its symmetric structure. The projection coefficient is the transformation invariance in this discretization, as well as the pixel position and the line position. We propose a block iterative image reconstruction algorithm by incorporating the geometry symmetry of the proposed discretization and projection onto convex sets (POCS) method. Experiments demonstrate the performance of the proposed discretization method and reconstruction algorithm in terms of image resolution and contrast and computing expense. This discretization method can also be applied to other image modalities.

8855-18, Session 4

One orthogonal multi-mask spectral image inversion algorithm for computational imaging spectrometry

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Computational imaging spectrometry (CIS) technology dispersed by one prism has been discussed in recent years. It has the advantage of high optical throughput , high resolution of spatial-spectral data-cube by rapid data inversion. However, CIS also has some disadvantages like aliasing in spatial-spectral image and insufficiency of sparse sampling which may reduce the accuracy of reconstructed spatial-spectral data-cube. Therefore, the spectral image inversion is one seriously crucial step for accomplishing its theoretical advantages.

In this paper, focusing on spectral image inversion, the algorithms, including image reconstruction, image compressed sensing and spectral image inversion theories were illustrated briefly . By pointing out the key issue of spectral image inversion ,one improved spectral image inversion algorithm with coded aperture function of orthogonal multi-frame is put forward, named as orthogonal multi-mask spectral image inversion algorithm (shortly for OMSII). OMSII algorithm relies on multi-frame exposures of CIS by the special mask. The newly designed coded aperture function has same characteristics with multi orthogonal and its self-recycle, some similar to the hadamard transform S recycle matrix.

According to computer simulation, compared to traditional spectral image inversion algorithms based on image compressed sensing theories , OMSII algorithm reconstructs spatial-spectral data-cube of higher quality, also the number of spectral band exceeds to ordinary hadamard transform spectral image inversion .Moreover, the spatial-spectral image aliasing is reduced. Based on the principle analysis with simulation results by virtue of OMSII algorithm, the key spatial-spectral sparsity of sampling data is well satisfied which improves the reconstruct accuracy a lot. So it has proved and provided one optimized route for CIS inversion algorithm, has with bigger feasibility for realizing the CIS theoretical advantages and ensuring CIS be more suitable technology for applications.

8855-19, Session 5

A recognition method in holographic data storage system by using structural similarity

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With the huge quantities of information increasing, the data storage requires more capacity to fill with the information. Then, the next generation of data storage, holographic data storage system (HDSS) can perform the task. The striking difference between HDSS and the conventional data storage (compact disc) is the record of page-oriented image. The page-oriented image would be influenced by the adverse effects such as thermal noise, misalignment and aberration in the HDSS. For reducing the effects, several methods such as image processing and error correction code have been developed in HDSS. In this article, we proposed a concept of the recognizable method in the image prepossessing of the HDSS by using structural similarity (SSIM) method. As a distorted image is received by the image sensor, the recognizable method utilizes a database of the reference image to compare with part of the distorted image and the degree of similarity between the images of the reference and distorted is determined by the SSIM method. Then, the reference image with maximum degree of similarity is regarded as binary data carried by the part of the distorted image.

8855-20, Session 5

Robustness of double random phase encoding spread-space spread-spectrum image watermarking technique

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In this paper the robustness of a recently proposed image watermarking scheme is investigated, namely the Double Random Phase Encoding spread-space spread-spectrum watermarking (DRPE SS-SS) technique. In the DRPE SS-SS method, the watermark is in the form of a digital barcode image which is numerically encrypted using a simulation of the optical DRPE process. This produces a random complex image, which is then processed to form a real valued random image with a low number of quantization levels. This signal is added to the host image. Extraction of the barcode, involves applying an inverse DRPE process to the watermarked image followed by a low pass filter. This algorithm is designed to utilize the capability of the DRPE to reversibly spread the energy of the watermarking information in both the space and spatial frequency domains, and the energy of the watermark in any spatial or spatial frequency bin is very small. The common geometric transformations and signal processing operations are performed using both the informed and the blind detections for different barcode widths and different quantization levels. The results presented indicate that the DRPE SS-SS method is robust to scaling, JPEG compression distortion, cropping, low pass and high pass filtering. It is also demonstrated that the bigger the barcode width is, the lower the false positive rate will be.

8855-21, Session 5

Monte Carlo simulation of neutron and other noise effects on beam position determination with real and simulated beam images at the National Ignition Facility

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Images obtained through charged coupled device (CCD) cameras in the National Ignition Facility (NIF) are crucial to precise alignment of the 192 laser beams to the NIF target-chamber center (TCC). Cameras in and around the target chamber are increasingly exposed to the effects of neutron radiation as the laser power is increased for high energy fusion experiments. NIF was carefully designed to operate under these conditions. The present work examines the degradation of the measured TCC camera position accuracy resulting from the effects of neutron radiation on the sensor and verifies operation within design specifications. Both synthetic and real beam images are used for measuring position degradation. Monte Carlo simulations based on camera performance models are used to create images with added neutron noise. These models predict neutron induced camera noise based on exposure estimates of the cumulative single-shot fluence in the NIF environment. The neutron induced noise images are used to measure beam positions on a target calculated from the alignment images with the added noise. The effects of this noise are also determined using noise artifacts from real camera images viewing TCC to estimate beam position uncertainty.

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8855-22, Session 5

Data mining with unsupervised clustering using photonic micro-ring resonators

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Data is commonly located in an optical format or moved through optical fiber in modern data centers. Therefore we review optical supervised and unsupervised systems for performing data mining operations. Chapter 14 in “Optical Computer Architectures” by A.D. McAulay (1992) describes an ultrafast optical dataflow correlator designed and constructed for the military to search for a known word or pattern in a supervised manner. More recently data mining makes extensive use of unsupervised learning (T. Kohonnen, book 1984) to find clusters in a database. The clusters provide significant information on relations between parameters in the database for the purpose of targeting advertising and planning. Micro-ring resonators have the potential to allow photonic circuits that match that of VLSI electronic circuits (SPIE 5595-48, McAulay et al). Therefore we propose that parameters corresponding to points in a database are converted from analog values to frequencies, as in done in the brain’s neurons (SPIE 6775-10, McAulay). We showed in SPIE 5809-49, (McAulay and Tong) that when micro ring resonators of close frequencies are placed near each other, the frequencies will move into step with each other through weak coupling. Therefore, in time, a group of resonators will form clusters of similar frequencies that will indicate the desired parameters having close relations.

8855-23, Session 5

The laser range profile and range imaging of a coarse cone

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Profile information about a three-dimensional target can be obtained directly by analyzing two-dimensional data of the laser range profile and the laser range imaging. A backscattering model of average signal power function for laser radar range imagery obtained by a short pulse laser for a coarse cone is presented in this paper. This model can analyze the laser range profile and range imaging which relate the average power seen by the receiver with laser pulse, target shape, optical scattering properties of surface material, incidence angle and other factors. The optical scattering property of the material is characterized by bidirectional reflectivity distribution function (BRDF). Based on BRDF, the optical scattering is considered. Simulation of the laser range profile and range imaging of a coarse cone is given, and the effects of some parameters including half-cone angle, surface optical scattering property, laser pulse width and incidence angle on the received power can be analyzed. Based on the results of the simulated model and theoretical analysis, the cone can be identified. The model can be used for demonstration of 3D laser radar system and can also be used to generate library of model data sets for automatic target recognition.

8855-24, Session 5

Filling gaps in Landsat ETM+ SLC-off images based on Bayesian estimation and non-local means

Peng Liu, Institute of Remote Sensing and Digital Earth (China)

Since its first launch in 1972, Landsat satellite series have been continuously collecting images of the earth from space. However, the scan-line corrector (SLC) of Landsat-7 Enhanced Thematic Mapper Plus (ETM+) sensor failed permanently on May 31st, 2003. It caused roughly 20% of the pixels to be un-scanned in any ETM+ images. In this paper, Landsat-5 TM images from similar dates and similar scenes are used as reference image to fill gaps of Landsat-7 SLC-off ETM+ images. We use the Bayesian theory to model the relationship between reference images of Landsat-5 and the target images of Landsat-7. Based on the maximum a posteriori criterion (MAP), we get an equation with respect to the pixels scanned in target image, pixel un-scanned in target images and the correspond pixels in the reference image. Based on the conditional posteriori probability, the un-scanned pixels in the target image are referred by the statistical characters of pixels from both neighborhood of target images and reference images. And the non-local means method is introduced into the MAP estimation. Based on non-local means, the most similar pixels to the target pixels are selected and weighted, and as the samples for the estimation of the un-scanned pixels in the target image. The redundant of texture in images and the spectral correlationship between Landsat5 images and Landsat-7 images make our MAP estimation very effective. We compared the proposed method with other state-of-the-art methods, and the better performances are shown in the experiments.

8855-25, Session 5

XOR/XNOR electro-optic logic circuit based on coupled-resonator-induced transparency

Yonghui Tian, Lei Zhang, Lin Yang, Institute of Semiconductors (China)

Electro-optic logic is a paradigm which employs the optical switch network to perform the logical operation. The status of each switch in the optical network is determined by an electrical Boolean signal applied to it. The operation of each switch is independent of the operations of other switches in the network and the operation result propagates in the network at the speed of light. The overall latency of the logic circuit is very small and all switches perform their operations almost simultaneously. Therefore, the electro-optic logic has a very high operation speed [1-4]. The presence of a coupled-resonator-induced transparency (CRIT) effect in parallelly coupled double microring resonators (MRRs) has been widely studied, and various applications based on the CRIT have been demonstrated [5-11]. As an application of the CRIT, we propose and demonstrate an electro-optic logic circuit which can implement XOR/XNOR operations using CRIT. The two electrical signals applied to the two MRRs carry the two operands of the logical operations, and the operation results are encoded on the output optical power. As proof-of-concept, a thermo-optic modulating scheme is employed with an operation speed of 10 kbps.

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8855-26, Session 5

Research progress of depth detection in vision measurement: a novel project of bifocal imaging system for 3D measurement

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Vision measurement technology has been widely used in the industrial measurement fields, which characterizes with the advantages of large range, high accuracy, high efficiency and non-contact measurement. The paper respectively reviews the recent research progresses of the monocular stereo vision measurement, the binocular stereo vision measurement and the multi-eye stereo vision measurement, and focuses on the existing approaches to obtain the depth information by the stereo vision. The advantages and disadvantages of the depth detection through the method of focus, defocus and zoom in monocular stereo vision are compared with each other. According to the above research background, a novel bifocal imaging measurement system based on the zoom method is proposed with the good performance of both the monocular and the binocular stereo vision. This imaging system consists of a primary lens and a secondary one with different focal length matching, in which two images can be acquired in the same exposure time. It can meet the large-range and high-resolution imaging requirements without time delay and imaging errors due to the multiple focus and zoom in the existing imaging system. At the same time, the system can meet the accuracy requirement under different measurement conditions through adjusting the different focal lengths of the secondary lens along the optical axis. This method is especially suitable for the online 3-D vision measurement, which can not only solve the real-time measurement problem of both static and dynamic targets, but also has an important significance for the industrial application.

8856-1, Session 1

Backward compatible JPEG lossy-to-lossless compression of medical data

Heng Chen, Geert Braeckman, Adrian Munteanu, Peter Schelkens, Vrije Univ. Brussel (Belgium) and iMinds (Belgium)

In this paper, we propose a novel reversible DCT-based lossy- to-lossless still image coding system for medical image data. We followed a two-layer design approach with traditional JPEG lossy compression being performed for the base layer, and lossless residual coding yields the enhancement layer. The enhancement layer bitstream is inserted into the base layer (JPEG) codestream and identified by a JPEG extension marker, in order to achieve backward compatibility.

From compression efficiency and functionality perspectives, JPEG 2000 is currently the best image codec available. JPEG-LS and JPEG XR yield competitive lossless compression performance, but none of them offers backward compatibility to the classical JPEG standard. Adding lossy-to-lossless functionality with our proposed system as an extension to the traditional JPEG standard, yields comparable lossless compression performance to that of JPEG-LS and JPEG XR while maintaining backward compatibility to the conventional JPEG. In this way, any imaging system, device, or application supporting JPEG can also decode the codestream produced by the new system without any modification.

8856-2, Session 1

Image enhancement for astronomical scenes

Jacob A. Lucas, Brandoch Calef, Boeing LTS Inc. (United States); Keith Knox, Air Force Research Lab. (United States)

Telescope images of astronomical objects and man-made satellites are frequently characterized by high dynamic range and low SNR. We consider the problem of how to enhance these images, with the aim of making them visually useful rather than radiometrically accurate. Standard contrast and histogram adjustment tends to strongly amplify noise in dark regions of the image. Sophisticated techniques have been developed to address this problem in the context of natural scenes. However, these techniques often misbehave when confronted with low-SNR scenes that are also mostly empty space. We compare two classes of algorithms: contrast-limited adaptive histogram equalization, which achieves spatial localization via a tiling of the image, and gradient-domain techniques, which perform localized contrast adjustment by non-linearly remapping the gradient of the image in a content-dependent manner. We extend these to include a priori knowledge of SNR and the processing (e.g. deconvolution) that was applied in the preparation of the image. The methods will be illustrated with images of satellites from a ground-based telescope.

8856-3, Session 1

Enhancement of image fusion methods

Yotam Ben-Shoshan, Yitzhak Yitzhaky, Ben-Gurion Univ. of the Negev (Israel)

Image fusion methods that can effectively combine information from different imaging sources have become more common due to the growing types and number of imaging sensors, and because it can be difficult for humans to effectively integrate visual information by viewing multiple displays separately. Hence, there is a need for combining streams with complementary information into one coherent representation in order to cope with the data overload. Fusion implementations are broadly common in medical, security, aviation, geoscience and other applications.

In this research we developed two novel techniques that can improve multi modal image fusion quality. The first technique is a decision algorithm that runs at the first stage of the fusion process. The algorithm determines the “polarity” of the images (i.e., assigning brighter or darker gray-level values to larger image intensities), under the assumption that fusion produces better results when the images are more similar. The second technique is a new approach for the composition stage in multi resolution fusion. Instead of fusing all pyramid levels using the combining method, we suggest to choose from the lowest levels in the pyramids only one image. The proposed techniques were implemented to various multi resolution fusion methods, including Lapalce pyramids, Ratio of Low Pass pyramids (ROLP) and Morphological pyramids. Pairs of thermal and either visual or near-IR images were employed in the fusion procedure. The experimental results indicate that the proposed methods lead to a better image fusion quality, with low computational cost, according to both objective and subjective fusion evaluations.

8856-4, Session 1

Adaptive design of composite correlation filters using multi-objective optimization

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In the design of composite correlation filters for pattern recognition, it is required to carefully choose a set of training templates for filter synthesis. The performance of these filters will highly depend on the proper selection of the training templates. Therefore, a strategy to choose the best training templates is desirable. In this work, we propose an adaptive algorithm for the design of composite correlation filters for pattern recognition. The algorithm, applies a genetic multi-objective optimization strategy to construct the optimal set of training templates for the synthesis of a composite filter with the best performance in terms of several conflicting metrics. To represent a potential solution within the feasible search space the proposed algorithm uses a variable length coding technique. Computer simulation results obtained by the proposed approach are presented and discussed in terms of several performance metrics, such as, discrimination capability, signal to noise ratio, and average similarity measure. These results are obtained by testing the performance of resulting composite filters in recognizing a geometrically distorted target in synthetic and real input scenes corrupted with overlapped and disjoint noise.

8856-5, Session 1

An improved approach to the cubic-spline interpolation

Tsung-Ching Lin, I-Shou Univ. (Taiwan); Shaohua Hong, Xiamen Univ. (China); Trieu-Kien Truong, I-Shou Univ. (Taiwan) and National Sun Yat-Sen Univ. (Taiwan); Lin Wang, Xiamen Univ. (China)

Cubic-spline interpolation (CSI) scheme is known to be designed to resample the discrete image data based on the least-squares method with the cubic convolution interpolation (CCI) function. It is superior in performance to other interpolation functions for digital image processing. In this paper, an improved cubic-spline interpolation (CSI) that combines the least-squares method with an eight-point cubic interpolation kernel is developed to improve the original CSI scheme. Either the FFT/Winograd DFT or the fast direct algorithm can also be used to perform the circular convolution needed in this improved CSI scheme as the original CSI scheme uses as well. Furthermore, its correlated image data and auto-correlated filter coefficients are also accurately calculated in this paper. Experimental results indicate that the proposed improved CSI scheme yields a much better quality of reconstructed image than existing interpolation algorithms including the original CSI scheme. For

an example of the gray 512*512 Lena image at same compression ratio of 4:1, the PSNR value of the reconstructed image using the proposed improved CSI scheme is higher by 2.3 dB, 1.7 dB, and 0.7 dB than linear interpolation, cubic-convolution interpolation, and the original CSI scheme, respectively.

8856-6, Session 1

Analysis of images obtained from space-variant astronomical imaging systems

Elena Anisimova, Jan Bednar, Martin Blažek, Peter Janout, Petr Pata, Karel Fliegel, Czech Technical Univ. in Prague (Czech Republic)

Most of the classical approaches to the measurement and modeling of electro-optical imaging systems rely on the principles of linearity and space invariance (LSI). In our previous research efforts we have focused on measurement and analysis of images obtained from a double station video observation system MAIA (Meteor Automatic Imager and Analyzer). The video acquisition module of this system contains wide-field input lens which contributes to the space-variant nature of the imaging system. For a precise astronomical measurement over the entire field of view, it is very important to comprehend how the characteristics of the imaging system can affect astrometric and photometric outputs. Space-variance as a property of an imaging system is studied in this paper in order to evaluate precision of astrometric and photometric results. This analysis is based on image data acquired in laboratory experiments and astronomical observations with the MAIA system. Methods for efficient calibration of this system to obtain precise astrometric and photometric measurements are also proposed.

8856-7, Session 1

Modified gradient descent method for image restoration

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In image restoration a function of two variables distorted by a known linear operator and additive noise is usually used. Numerous restoration techniques optimized with respect to different were introduced. It was shown that to solve the problem one can be used not only metrical characteristics but also topological ones of the function of two variables. Kronrod proposed to describe a function of two variables with two variations. One of them is a total variation for continuously differentiable functions. Another one is referred to as a linear variation. For continuous functions the linear variation is the sum of numbers of regular level set components for all levels. The linear variation is a topological characteristic of a function of two variables whereas the total variation that is a metrical characteristic of a function. The proposed topological method of image restoration modifies the result of the total variation-based method in order to obtain a given number of linear variations (connected components) at the output. It order to explain the ability of the proposed method to improve the restoration performance of the total variation-based method, we analyze the position of local maxima and minima of the function obtained with the gradient descent algorithm. A number of statements about the behavior of the local maxima and minima of the restored function with the total variation-based method for the case of horizontal blurring are proved. Next, we provide a formal explanation why the proposed method improves the restoration performance of the total variation-based method. Computer simulation results are provided to illustrate the performance of the proposed algorithm for restoration of degraded images.

8856-8, Session 2

Quantized embeddings: an efficient and universal nearest neighbor method for cloud-based image retrieval

Shantanu Rane, Petros T. Boufounos, Anthony Vetro, Mitsubishi Electric Research Labs. (United States)

Efficient cloud-based image retrieval requires image features that have low communication overhead, provide an accurate representation of the image, remain robust to misalignment and scale, and allowing fast cloud-based matching with minimal updates to the parameters of the client's algorithm. Most image feature spaces provide only a subset of these desired properties, and are restricted to a particular class of images; E.g., a feature space that is discriminative for searching buildings may not be as useful for discriminating medical images. Furthermore, a feature space may be discriminative for a given class of images, but may incur a large communication overhead. In this paper, we propose to extract quantized random projections of the image features under consideration, transmit these to the cloud server, and perform matching in the space of the quantized projections.

The advantage of using quantized random projections is that, once the underlying feature extraction algorithm is chosen for maximum discriminability and retrieval performance (e.g., SIFT, or eigen-features, or simply the image pixels), the random projections can guarantee a bit-rate efficient representation, as well as fast server-based matching with negligible loss in accuracy. These properties follow from the Johnson-Lindenstrauss Lemma, which states that pair-wise distances between the underlying feature vectors are preserved in the corresponding quantized embeddings.

We report experimental results of image retrieval on two image databases that employ different feature spaces, one uses SIFT features and the other uses face features extracted from the Viola-Jones face detector. For both these feature spaces, using quantized embeddings as mentioned above results in accurate image retrieval with the added advantages of bit-rate efficiency and speed of matching, even though the underlying feature spaces themselves would not have provided these advantages.

8856-9, Session 2

Cloud-based image denosing

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Traditional image denoising methods recover a digital image from its noisy version by exploring the statistical features inside the noisy image only. They work well when a target image is slightly noisy, but unable to provide a clear result at high noise levels. In this paper, we propose a novel image denoising scheme which recovers an image by exploiting the correlations between the noisy image and the images retrieved from the Cloud. Given a noisy image, we first retrieve the relevant images based on the feature-level similarity. These images are then geometrically aligned to the noisy image to enhance the global statistical correlation. Using the aligned images as references, we recover the image by our proposed patch-level noise removal, in which the local characteristic of each noisy patch is estimated from its similar patches extracted from the references. Finally, the recovered noise free patches are blended together producing the desired noise free image. Experimental results demonstrate that our scheme achieves significant improvement compared with state-of-the-art methods in terms of both objective and subjective qualities.

8856-10, Session 2

vPresent: a cloud based 3D virtual presentation environment for interactive product customization

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In modern society, many companies offer customized products to their customers. There are two major challenges in providing customized products. First, product providers need to effectively present their products to the customers who may be located in any geographical area. Second, customers need to be able to provide their feedbacks on the products in real-time. However, the traditional text-based presentation cannot effectively convey sufficient information for the products or efficiently adjust product design according to customers' real-time feedbacks. In order to address the challenges, we propose vPresent, a cloud based 3D virtual presentation environment, in this paper. In vPresent, the product specialists can show the 3D virtual product to the remote customers and dynamically customize the product based on customers' feedbacks, while the customers can provide their opinions in real time when they are viewing a vivid 3D visualization of the product. Since the proposed vPresent is a cloud based system, the customers are able to access the customized virtual products from anywhere at any time, via desktops, laptops, or even smart phones. The proposed vPresent is expected to effectively deliver 3D visual information to customers and provide an interactive design platform for the development of customized products.

8856-11, Session 2

Low-delay cloud based rendering of free viewpoint video for mobile devices

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Free viewpoint video (FVV) provides immersive experiences in a truly seamless environment. Cloud computing facilitates the possibility to watch the FVV on mobile devices through the remote rendering in which the synthesis view is rendered in cloud server and transmitted to mobile devices. However, how to reduce the interaction delay during the viewpoint switching is a challenging problem in the remote rendering. In this paper, we propose a low-delay cloud-based FVV rendering framework to support FVV on mobile devices with satisfactory video quality and low interaction delay. In our framework, the rendering allocation scheme is proposed in which the local rendering is introduced on mobile devices during the viewpoint switching to conceal the interaction delay. To support the local rendering, the side information is generated based on the viewpoint prediction and 3D warping rule in cloud and then compressed by an edge-based coding scheme. The experiment results show that the proposed remote rendering framework can improve the quality of experience with improved free viewpoint video quality and low interaction delay on mobile devices.

8856-12, Session 2

Mobile panorama view from single picture

Hongzhi Li, Columbia Univ. (United States); Wenwu Zhu, Tsinghua Univ. (China)

Panorama view provides people an informative and natural user experience to represent the whole scene. The advances on mobile augmented reality, mobile-cloud computing, and mobile internet can enable panorama view on mobile phone with new functionalities, such as anytime anywhere query where a landmark picture is and what the whole scene looks like. To generate and explore panorama view on mobile devices faces significant challenges due to the limitations of computing capacity, battery life, and memory size of mobile phones, as well as the bandwidth of mobile internet connection. To address the challenges, this paper presents a novel cloud-based mobile panorama view system that can generate and view panorama view on mobile devices from a single picture, namely "mPano". In our system, first, we propose a novel iterative multi-modal image retrieval (IMIR) approach to get spatially adjacent images using both tag and content information from the single picture. Second, we propose a cloud-based parallel server synthing approach to generate panorama view in cloud, against today's local-client synthing that is almost impossible for mobile phones. Third, we propose predictive-cache solution to reduce latency of image delivery from cloud server to the mobile client. We have built a real mobile panorama view system and perform experiments. The experimental results demonstrated the effectiveness of our system and the proposed key component technologies, especially for landmark images.

8856-13, Session 3

Augmented video calls on mobile devices

Fengqing Zhu, FutureWei Technologies, Inc. (United States)

No Abstract Available

8856-14, Session 3

Integrating eye tracking and motion sensor on mobile phone for interactive 3D display

Shang-Hong Lai, National Tsing Hua Univ. (Taiwan)

No Abstract Available

8856-15, Session 3

Architecting social TV

Hari Kalva, Florida Atlantic Univ. (United States)

No Abstract Available

8856-16, Session 3

Study on panel sharpening for different color spaces and use cases

Min Dai, Qualcomm Inc. (United States)

No Abstract Available

8856-17, Session 3

Enabling QoE-based scheduling via PSNR time series prediction for video teleconferencing

Lianping Ma, Yuriy A. Reznik, Rahul Vanam, Gregory Sternberg, InterDigital, Inc. (United States)

No Abstract Available

8856-18, Session 3

Improving efficiency of mobile video streaming by adaptation to user behavior and viewing conditions

Yuriy A. Reznik, InterDigital, Inc. (United States)

No Abstract Available

8856-19, Session 3

The future of 3D and video coding in mobile and the internet

Lazar M. Bivolarski, LZ Associates (United States)

This paper presents a review of the current trends in 3D and video coding in the mobile environment and its continued fusion with the Internet. The technology advances in recent years brought increased interest in the 3D video. There is significant growth in consumer devices capable of 3D including a number of 3D cinema screens. The 3D and video are increasingly considered the most promising technologies fueling the growth of home entertainment. The technological advances and the increased market interest in turn stimulate the new research directions as well as industry efforts in standardization that capture the dynamic of this field. New video standards are emerging and being deployed to facilitate the media content delivery. Real-time collaborative environments and services make are being distributed of heterogeneous networks that use the new 3D content formats and deice rendering capabilities. New search engines and capabilities facilitate content search in a complex virtual environments. The sophisticated representation and delivery of 3D media on the Internet affects the development of new content acquisition and presentation devices that includes mobile devices as well. This environment presents new challenges for video coding of the content and opportunities for future advances.

8856-101, Session 3

Temporally coherent 4D video segmentation for teleconferencing

Jana Ehmann, Onur G. Guleryuz, FutureWei Technologies, Inc. (United States)

We develop an algorithm for 4-D (RGB+Depth) video segmentation targeting immersive teleconferencing applications on emerging mobile devices. Our algorithm extracts users from their environments and places them onto virtual backgrounds similar to green-screening. The virtual backgrounds increase immersion and interactivity, relieving the users of the system from distractions caused by disparate environments. Commodity depth sensors, while providing useful information for segmentation, result in noisy depth maps with a large number of missing depth values. By combining depth and RGB information, our work significantly improves the otherwise very coarse segmentation. Further imposing temporal coherence yields compositions where the foregrounds seamlessly blend with the virtual backgrounds with minimal flicker and other artifacts. We achieve said improvements by correcting the missing information in depth maps before fast RGB-based segmentation, which operates in conjunction with temporal coherence. Simulation results indicate the efficacy of the proposed system in video conferencing scenarios.

8856-20, Session 4

A comparison of Fisher vectors and Gaussian supervectors for document versus non-document image classification

David C. Smith, National Security Agency (United States); Keri Kornelson, The Univ. of Oklahoma (United States)

This research addresses the document vs. non-document image classification problem. The ability to accurately select document images from a data stream containing a wide variety of image types, e.g., animals, scenes, faces, etc., as well as document images intended for subsequent presentation to an OCR system is higly desirable. Without pre-selection of document images, valuable computer resources are wasted performing OCR on the non-document images, and human effort is needlessly expended or automatic queries are unnecessarily performed attempting to glean information from unintelligible OCR transcripts. This is particularly true for high volume OCR systems which process thousands of images daily. Fisher vectors represent images as gradients with respect to the parameters of a global generative probability model (e.g., a Gaussian Mixture Model, GMM) of low level image descriptors (e.g., Sift or Surf). Fisher vectors have demonstrated state-of-the-art performance for object categorization on the Caltech 256 and PASCAL VOC 2007 data sets using low cost linear SVM classifiers. A competing method, Gaussian supervectors, represent images by soft clustering the low level image descriptors according to the posterior probabilities that an observed descriptor comes from a particular Gaussian mixture. Normalized averages of the descriptors in each cluster are computed and concatenated to form a Gaussian supervector. For scene categorization, Gaussian supervectors have significantly improved upon the performance of the traditional bag-of-visual words representation. For the document vs. non-document image classification problem, we compare results obtained when a linear SVM is applied to Fisher vector and Gaussian supervector image representations. We also consider a much simpler classification scheme based only on matching local image descriptors, without recourse to visual vocabularies or generative probalistic models.

8856-22, Session 4

On selecting reference image models for anomaly detection in industrial systems

Xinhua Xiao, Jin Quan, Univ. of Cincinnati (United States); Andrew Ferro, GE Aviation Systems (United States); Chia Yung Han, Xuefu Zhou, William G. Wee, Univ. of Cincinnati (United States)

Automatic X-ray inspection of industrial parts usually uses reference-based methods, in which a set of model images or statistics extracted from the model image set are selected as the benchmark. Based on these methods, many systems are developed and are used extensively for anomaly detection. However, the performance of these systems relies heavily on the model image set. Thus, the selection of the model images is of importance. This paper presents an approach for automatically selecting a set of model images to be used in a reference-based assisted defect recognition (ADR) system for anomaly detection of turbine blades of jet engines. The proposed approach to generating a model image set is based on feature extraction. Features are extracted from callout images of the ADR system, including potential defect indication type, size and location. Experimental results show that the proposed approach is fast and a low false alarm rate with acceptable detection rate is ensured. Moreover, the approach is applicable to different blade types and varied views of the blade. Further validation shows that the approach can be applied to the update of the model image set when more images are generated from new blades.

8856-23, Session 4

Adaptive pattern for autonomous UAV guidance

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The research done at the Fraunhofer IOSB in Karlsruhe within the AMFIS project is focusing on a mobile system to support rescue forces in accidents or disasters. The system consists of a ground control station which has the capability to communicate with a large number of heterogeneous sensors and sensor carriers and provides several open interfaces to allow easy integration of additional sensors into the system. Within this research we focus mainly on UAV such as VTOL (Vertical takeoff and Landing) systems because of their ease of use and their high maneuverability. To increase the positioning capability of the UAV, different onboard processing chains of image exploitation for real time detection of patterns on the ground and the interfacing technology for controlling the UAV from the payload during flight were examined. The earlier proposed static ground pattern was extended by an adaptive component which admits an additional visual communication channel to the aircraft. For this purpose different components were conceived to transfer additive information using changeable patterns on the ground. The adaptive ground pattern and their application suitability had to be tested under external influence. Beside the adaptive ground pattern, the onboard process chains and the adaptations to the demands of changing patterns are introduced in this paper. The tracking of the guiding points, the UAV navigation and the conversion of the guiding point positions from the images to real world co-ordinates in video sequences, as well as use limits and the possibilities of an adaptable pattern are examined.

8856-24, Session 4

On the coding of interlace scanned content in HEVC

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No abstract available

8856-25, Session 4

Automatic defect detection in video archives: application to Montreux jazz festival digital archives

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Archival of audio visual data bases has become an important discipline in multimedia. Various defects are typically present in such archives. Among those one can mention recording related defects such as interference between audio and video signals, optical related artifacts, those related to recording and play out such as horizontal lines, and drop outs, as well as those due to digitization such as diagonal lines. An automatic or semi-automatic detection to identify such artifacts is useful, especially for large data bases. In this paper we propose two automatic algorithms for detection of horizontal and diagonal lines, as well as drop outs that are among the most typical artifacts. We then evaluate the performance of these algorithms by making use of ground truth scores obtained from human subjects.

8856-26, Session 4

Early forest fire detection using mid-wave and long-wave infrared cameras

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Long-wave IR (LWIR) is commonly referred to as the “thermal infrared” region where thermal sources are captured without the need of, or interference from, external light/thermal sources. The mid-wave IR (MWIR) displays characteristics in between those of the thermal and reflected infrared regions, where both black-body radiation and its reflections can be detected. This paper examines the differences in the cooled MWIR and LWIR imagery obtained simultaneously from several staged test forest fires. It is shown that the resulting difference images can be effectively exploited to detect and classify heat plumes which are expelled at the early stages of the forest fire. The heat plume detection performance of this dual IR band approach is compared with that of a single IR band approach which is based on application of wavelet transform to consecutives video frames.

8856-27, Session 4

A framework for objective evaluation of privacy filters in video surveillance

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The use of video surveillance is increasing to fight against criminal and terrorist activities. At the same time, video surveillance brings various complications regarding protection of privacy of people and goods under surveillance. Several solutions have been proposed in the past to overcome if not completely, at least partially, the degree of impact on invasion of privacy, while still maintaining reasonable mechanisms for monitoring, tracking and surveillance.

In this paper, we propose a new framework for objective evaluation of privacy filters, as en extension of a prior work based on subjective evaluation. After a discussion of the architecture and process for the objective evaluation, the performance of the proposed approach is compared to subjective evaluations from various points of views, and conclusions are drawn.

8856-28, Session 4

Video coding standards performance comparison

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Comparing of video codecs has been a subject of many studies of the years. Various parameters and content are used to extract performance of the codecs for specific environments and use cases. The performance evaluation is usually centered on common test conditions to minimize the variation in the interpretation of the results. The overall quality then is measured as relation between the compression the compression ratio the absolute arithmetic difference measured with PSNR. This paper analyses the comparison between different coding schemes and compares the quality as the function of the coding scheme complexity and the relative content complexity. The normalization of both complexities and the coding efficiency with PSNR then will represent a better basis of comparison between the codding schemes since it will include the cost of the efficiency achieved via specific coding scheme. The paper analyses the various quality metrics and presents the value of specific quality metric applicability in the corresponding use cases.

The comparing of different coding schemes is presented using over the same content without a need for synchronized test conditions due to the content and coding scheme the complexity normalization.

8856-29, Session 5

Analysis of view synthesis prediction architectures in modern coding standards

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Depth-based 3D formats are currently being developed as extensions to both AVC and HEVC standards. The availability of depth information facilitates the generation of intermediate view points for advanced 3D applications and displays, and also enables more efficient coding of the multiview input data through view synthesis prediction techniques. This paper outlines several approaches that have been explored to realize view synthesis prediction in modern video coding standards such as AVC and HEVC. The benefits and drawbacks of various architectures are analyzed in terms of performance, complexity, and other design considerations.

8856-30, Session 5

Neighboring block based disparity vector derivation for multiview compatible 3D-AVC

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3D-AVC, which is being developed under JCT-3V, significantly outperforms the Multiview Video Coding plus Depth (MVC+D), which doesn't have new macroblock level coding tools compared to Multiview video coding extension of H.264/AVC (MVC). However, when configuring 3D-AVC to support multiview compatibility, texture views are decoded without depth information, and the performance of the current 3D-AVC becomes only comparable to MVC+D. The problem is caused by the lack of disparity vectors between views which can be converted only from depth views in 3D-AVC. In this paper, an efficient disparity vector derivation method utilizing only the information of texture views is proposed. Motion information of neighboring blocks is used to determine a disparity vector for a macroblock, and the derived disparity vector is efficiently used for existing coding tools in 3D-AVC. The proposed method enables increasing the performance of 3D-AVC in the multiview compatible mode substantially, about 20% bit-rate reductions for texture coding.

8856-31, Session 5

Depth estimation from multiple coded apertures for 3D interaction

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In this paper, we propose a novel depth estimation method from multiple coded apertures for 3D interaction. A flat panel display is transformed into lens-less multi-view cameras which consist of multiple coded apertures. The sensor panel behind the display captures the scene in front of the display through the imaging pattern of the modified uniformly redundant arrays (MURA) on the display panel. To estimate the depth of an object in the scene, we first generate a stack of synthetically refocused images at various distances by using the shifting and averaging approach for the captured coded images. And then, an initial depth map is obtained by applying a focus operator to a stack of the refocused images for each pixel. Finally, the depth is refined by fitting a parametric focus model to the response curves near the initial depth estimates. To demonstrate the effectiveness of the proposed algorithm, we construct an imaging system to capture the scene in front of the display. The system consists of a display screen and an x-ray detector without a scintillator layer so as to act as a visible sensor panel. Experimental results confirm that the proposed method accurately determines the depth of an object including a human hand in front of the display by capturing multiple MURA coded images, generating refocused images at different depth levels, and refining the initial depth estimates.

8856-32, Session 5

Automatic camera to laser calibration for high accuracy mobile mapping systems using INS

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A mobile mapping system (MMS) is a mobile multi-sensor platform developed by the geoinformation community to support the acquisition of huge amounts of geodata in the form of georeferenced high resolution images and dense laser clouds. Since data fusion and data integration techniques are increasingly able to combine the complementary strenghts of different types of sensors, the external calibration of a camera to a laser rangefinder is a common pre-requisite on today's mobile platforms. The methods of calibration are often poorly documented, are time-consuming, demand expert knowledge and often require a carefully constructed calibration environment.

A new methodology is studied and explored to provide a high quality external calibration for a camera to a laser range finder which is automatic, easy to perform, robust and fool proof.

The positioning system used on the mobile platform is an Applanix POSLV 420, the mounted camera is a Point Grey color video camera, the laser is a 2D RIEGL LMS-Q120, both synchronized with the POSLV 420 system. The method presented here, uses a portable, standard ranging pole which needs to be positioned on a known ground control point. For calibration, a well studied absolute orientation problem needs to be solved. In this study, the use of the inertial relative movements will be explored to collect more useful calibration data. This results in a better intersensor calibration allowing better coloring of the clouds and a more accurate depth mask for images, especially on the edges of objects in the scene.

A few benchmarking tests are done under various lighting conditions which proves the methodology's robustness, by showing subpixels accuracy for projected laser data on the images.

8856-33, Session 5

Obliquity effect removal in 3D object reconstruction

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We have been working in the reconstruction of 3D objects, using the reflectivity of the material to obtain the depths with Gaussian models. In this kind of reconstruction there is a problem of obliquity outside the paraxial area due to the nature of the source. To solve this obliquity problem, we use the Phong's illumination model and the angular aperture of the source to compensate it. In our approach we take two images of a planar object at different distances so the system can calculate the compensation mesh to rebuild the object and thus eliminate this obliquity of the reconstructed object. We present comparisons of this improved method against Gaussian models and reconstructions using the LFS system.

8856-34, Session 5

Multiview synthesis for auostereoscopic displays

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No Abstract Available

8856-35, Session 5

Single pass image warping method with anisotropic filter

Vladimir Lachine, Gregory Smith, Louie Lee, Qualcomm Inc. (Canada)

Conventional image capture and display devices are prone to various form of optical artifacts. These artifacts are inherent to the none ideal behavior of the various optical elements such as sensors, displays, lens, prisms, mirrors, light sources. These optical distortions may be corrected digitally by image warping technology.

Image warping may be defined as a process of dynamically resampling a regularly spaced input image to produce a none regular spacing output image.

In this paper, one-pass algorithm for digital image warping is presented. It is based on anisotropic circularly symmetric antialiasing filtering over elliptical or rectangular footprint. It is shown that developed design provides flexibility and better image quality than known two-pass methods. The proposed algorithm may be embedded into display processor for optical distortion corrections both at image acquisition and displaying sides. It includes luminance and chromaticity non-uniformity correction as well.

8856-36, Session 5

A post-alignment method for stereoscopic movie

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No Abstract Available

8856-37, Session 6

Low complexity video coding using SMPTE VC-2

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This paper describes the recently standardized High Quality, “HQ” profile of the SMPTE VC-2 codec, designed for low complexity and low latency applications. It presents experimental results for a selection of low complexity coding parameters for both RGB and YCbCr (4:4:4) coding. VC-2 HQ’s motivating application was video production and archiving, but it can also embrace other applications such as texture coding, high dynamic range, and lossless coding.

VC-2 HQ is an intra frame wavelet codec. It supports a range of coding parameters such as a choice of wavelet kernels, wavelet depths and size of coded image region (analogous to the transform size in a block transform codec). This paper specifically investigates the low complexity coding parameters of 2 and 3 level Haar and LeGall wavelet kernels, for image regions of 4x4 and 8x8 pixels.

Whereas texture codecs typical target a fixed compression ratio with limited bit depth, VC-2 HQ provides greater flexibility supporting compression ratios from 8:1 to lossless coding at greater bit depth. This paper focuses on the design choices made for low complexity, such as the absence of prediction and the type of entropy coding. Results are presented showing the effect of some of these choices. It also describes the partitioning of wavelet coefficient, which is different from a block transform codec. This allows it support a simple quantization scheme, thereby avoiding buffering and facilitating low latency. The resulting spatially varying quantization exploits psychovisual masking and supports coding higher dynamic range signals.

8856-38, Session 6

Performance evaluation of phase-based correspondence matching on GPUs

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Image correspondence is one of the important key techniques in many fields such as image sensing, video signal processing, computer vision, etc. Especially, 3D measurement using stereo vision requires an accurate stereo correspondence algorithm, since the accuracy of 3D measurement depends on that of image correspondence between a stereo image pair. The computation time of image correspondence is also important in practical applications of 3D measurement using stereo vision.

To achieve high-accuracy 3D measurement, we have proposed a high-accuracy stereo correspondence matching method using Phase-Only Correlation (POC). Using our method, we have also developed a passive 3D measurement system, whose accuracy is comparable with active 3D measurement systems. On the other hand, the application range of POC-based correspondence matching is limited, since many corresponding point pairs are required for measuring fine 3D structure of an object even though the computational cost of POC-based correspondence matching is high.

Addressing this problem, we propose a Graphics Processing Unit (GPU) implementation of the POC-based correspondence matching method and implementation techniques for GPU architecture. Through experiments using a variety of GPUs of different vendors and architecture, we demonstrate that the proposed approach is high-speed and high-efficiency compared with the CPU implementation and provide a detailed performance analysis of the GPU implementation. We also develop a real-time 3D measurement system using the proposed approach and demonstrate its effectiveness.

8856-39, Session 6

Comparison of CPU and GPU based coding on low-complexity algorithms for display signals

Thomas Richter, Univ. Stuttgart (Germany); Sven Simon, Department of Parallel Systems, University of Stuttgart (Germany)

Graphics Processing Units (GPUs) are freely programmable massively parallel general purpose processing units and thus offer the opportunity to off-load heavy computations from the CPU to the GPU. One application for GPU programming is image compression, where the massively parallel nature of GPUs promises high speed benefits. This article analyzes the predicaments of data-parallel image coding on the example of two high-throughput coding algorithms designed particularly for the online-compression of monitor signals. The codecs discussed here, a wavelet based SPIHT codec and a Hadamard based embedded codec, were designed to answer a call from the Video Electronics Standards Association (VESA), and require only minimal buffering at encoder and decoder side while avoiding any pixel-based feedback loops limiting the operating frequency of hardware implementations.

Comparing CPU and GPU implementations of the codes show that GPU based codes are usually not considerably faster, or perform only with less than ideal rate-distortion performance. Analyzing the details of this result provides theoretical evidence that for any coding engine either parts of the entropy coding and bitstream build-up must remain serial, or rate-distortion penalties must be paid when offloading all computations on the GPU.

8856-40, Session 6

Compact opto-electronic engine for high-speed compressive sensing

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The resource efficiency of compressive sensing (CS) enables the computational construction of images from far fewer measurements than what is usually considered necessary by the Nyquist–Shannon sampling theorem. There is now a vast literature around CS mathematics and applications since the development of its theoretical principles about a decade ago that includes quantum information to optical microscopy to seismic imaging. In the application of shortwave infrared imaging, we have developed cameras based on the CS "single-pixel" camera architecture. This architecture comprises an objective lens to image the scene onto a Texas Instruments DLP micromirror array (DMD), which by modulating the image with its individually controllable mirrors, projects the image onto a selected basis set. Optics following the DMD collects and focuses the image on the detector. We have also developed higher frame rate cameras with a similar architecture that utilize multiple detectors working in parallel.

While the design of a CS camera is straightforward conceptually, its bench top implementation is a project that requires significant development efforts in optics, electronics, hardware and software, particularly if high efficiency and high-speed operation are required. We describe development of a high-speed CS engine in the form of a lab-ready workstation where custom measurement patterns are loaded at speeds up to 32kHz and custom reconstruction algorithms can be quickly implemented in experiments. Our work includes optical path design, FPGA's for DMD pattern generation, and circuit boards for front end data acquisition, ADC and system control packaged in a compact workstation.

8856-42, Session 6

Joint estimation and tracking of objects in a single camera using EM-EKF

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Tracking objects in dynamic scene is an interesting area of research and it has applications in many areas like surveillance, missile tracking system, virtual reality and robot vision. Objects in real world exhibit complex interactions with each other. When captured in a video signal, these interactions manifest themselves as intertwining motions, occlusion and pose changes. A video tracking system should track these objects in this complex interactions smoothly. This paper presents a new joint method for tracking moving objects in outdoor and indoor environment. This joint method uses recursive expectation-maximization (EM) incorporated with Extended Kalman Filter (EKF) to estimate, fuse and track the object simultaneously than doing it in two different steps. This combined approach provides more realistic solution to the problem by including all the parameters in state variables and assigning the track based on the likelihood of the objects position. Thereby, outperforming the conventional method of treating it as two different problems. We have tested our algorithm with standard data set and real time video sequences collected from indoor environment. On testing this algorithm with PETS 2001 data set we find that 14 out of 17 objects are accurately tracked with the accuracy of 82% and Occlusion Success Rate (OSR) of 75% with frames processed at a rate of 25fps. With real time video sequence, our approach successfully tracks the objects with occlusions with tracking accuracy of 95% and OSR of 80%. This method successfully tracks objects with occlusions, orientations and intertwining motion with better accuracy and low computational cost.

8856-43, Session 6

A fast kernel tracking algorithm based on local gradient histograms

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The tracking task in a video sequence has many and diverse approaches, and so many ways to solve it. Many different problems are usually solved: detection and localization of the tracked object in the scene, invariance to different movement directions of the object, situations when the object goes in and out the scene, occlusion and so on. The first thought for solving it could be to run an image matching algorithm over every frame of the sequence. However, nowadays the frame rates are as low as 30 FPS (frames per second) to as high 300 FPS in special devices as high speed cameras; so, solving an image matching problem at least thirty times per second is a tiresome and costly task for any machine. To reduce processing, memory and time costs, many algorithms have been proposed. These algorithms can be classified as follows: point trackers, kernel trackers, and silhouette trackers. Point trackers take advantage of repeatable interest points over the first frames of the sequence, allowing the extraction of information about direction as well as speed. Kernel trackers use sliding windows to locate the object using histograms and other area information techniques; once the object is located the search area is reduced to that of the neighborhood of the object. The silhouette trackers extract the information to the contour of the object and follow this contour over the frame sequence. In this work, we propose a kernel tracking algorithm based on a local gradient histogram's matching algorithm and recursive calculation of the object position over the video sequence.

8856-44, Session 6

Real-time object tracking using digital correlation filtering and state prediction

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A real-time tracking system based on adaptive correlation filtering, is proposed. The system is able to estimate at high-rate the position of a given target at any time instant by taking into account information of past and present scene-frames. The position of the target is estimated with the help of a bank of composite correlation filters with complex constraints, trained with an iterative algorithm. The filter bank, is applied to a small region of the observed scene that is updated at each frame according to a state predictor which is based on the motion model of the target in a two-dimensional plane. Furthermore, the filter bank is able to modify the number of required filters for each frame in order to reduce computational complexity. The proposed system is implemented on a graphics processing unit to take advantage of massive parallelism. As result, we can perform object tracking in real-time. Computer simulation results obtained with the proposed system in synthetic and real noisy scenes, are presented and discussed in terms of tracking accuracy and real-time operation efficiency. Tracking accuracy is characterized by discrimination capability and location errors, whereas real-time operation efficiency is measured by the average processed frames per second.

8856-45, Session 7

QoE for telemedicine: challenges and trends

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To really improve the access, efficiency, effectiveness and quality of clinical processes, telemedicine, with the sharing of digital data (i.e. physiological signals, 2D/3D images and videos) should adhere to the same standards of quality and usability, as that in traditional healthcare. This paper proposes a survey of some key issues and trends associated to an emerging quality measurement called Quality of Experience (QoE) in telemedicine. Although, the quality of services (QoS) in telemedicine has been quite investigated of late, the QoE is in its infant's age and should not be assimilated to QoS. Considered as the most important factor adoption of telemedicine, QoE studies should be conducted with an appropriate methodology incorporating user involvement and digital data and their relation with QoS should be identified.

We first present the services offered by telemedicine and underline the significance of QoE for tele-diagnosis and tele-surgery including digital data from different acquisition modalities. Next, we identify and analyze the influencing factors such as application area, application purpose (emergency care, acquisition assistance, second opinion, education...), content type (data specificities depending on acquisition modality), context of use (offline/real time, interactivity...), and user's state (stress, expertise...), that we have to consider for a relevant QoE measurement in telemedicine. At last, we present different solutions in the framework of QoE measurement including offline tools for benchmarking (oriented Perceptual Difference Model, Model Observer) and real time tools for monitoring (video and audio quality assessment with full-reference metrics and parametric metrics).

8856-46, Session 7

Classification of microcalcifications using micro-CT

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Microcalcifications are tiny spots of calcium deposit that often occur in female breasts. Microcalcifications are common in healthy woman, but they often are an early sign of breast cancer. On a mammogram, the current standard of care for breast screening, calcifications appear as tiny white dots. They may occur scattered throughout the breast or grouped in clusters. Radiologists determine the suspiciousness based upon several factors, including position, frequency, grouping, evolution compared to prior studies and shape. In this paper, we study micro-CT images of biopsy samples containing microcalcifications. The scanner delivers 3D images with a voxel size of 12µm, i.e. ca. 8 times the spatial resolution of a contemporary digital mammogram. We propose an automated binary classification method of the samples, based upon shape analysis of the microcalcifications. The study is performed on a set of 50 benign and 50 malign samples preserved in paraffin. The ground truth of the classification is based upon anapathological investigation of the paraffin blocks.

8856-47, Session 7

Motion compensation of optical mapping signals from isolated beating rat hearts

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Introduction

Optical mapping is a well established technique for recording monophasic action potential traces on the epicardial sur-face of isolated hearts, [1]. This measuring technique offers a high spatial resolution but it is sensitive towards myocar-dial motion. Motion artifacts occur because the mapping between a certain tissue portion sending out fluorescent light and a pixel of the photodetector changes over time. So far this problem has been adressed by suppressing the motion or ratiometric imaging, [2, 3]. We developed a different approach to compensate the motion artifacts based on image registration.

Methods

Five rat hearts were excised and stained with Di-4-ANEPPS during cardioplegia. They were brought to beating auton-omously before current-controlled stimulation was applied at the apex. After 20 minutes 2,3-Butanedione Monoxime (BDM) was given for mechanical uncoupling. Light emitting diodes were used for excitation (peak wavelength at 530 nm). Optical mapping data in all three phases was recorded with a sCMOS camera (295 fps, long pass emission filter at 610 nm). The cardiac motion was determined from the images in two steps: First the translation and shearing were determined using a 2D affine registration algorithm. Afterwards the deformation was calculated with a nonrigid demon's algorithm, [4].

Results

We compared traces of the motion compensated fluorescence difference signal with traces recorded after applying BDM. We could determine a significant reduction of motion artefacts.

Conclusion

Optical mapping of rat hearts in combination with optical motion tracking makes it possible to monitor both myocardial motion and excitation propagation with high spatial resolution.

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8856-48, Session 7

Automated estimation of hip prosthesis migration: a feasibility study

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A common complication associated with hip arthoplasty is prosthesis migration, and cemented components with a migration greater than 0.85mm within the first six months after surgery, are an indicator for prosthesis failure.

Currently, prosthesis migration is evaluated using X-ray images, which can only estimate migrations larger than 5mm.

We propose an automated method for estimating prosthesis migration more accurately, using CT images and image registration techniques. We report on the results obtained using an experimental set-up, in which a metal prosthesis can be translated and rotated w.r.t. a cadaver femur, over distances and angles, applied using a combination of positioning stages. 30 high-resolution helical CT images were acquired for prosthesis translations ranging from 0.05mm to 4mm, and rotations ranging from 0.3° to 3°.

Images are first preprocessed to reduce artifacts. Bone and prosthesis are extracted using consecutive thresholding and morphological operations. Two registrations are performed, one aligning the bones and the other aligning the prostheses. The migration is estimated as the difference between the found transformations. We use a robust, multi-resolution, stochastic optimization approach, able to deal with the metal artifacts, and compare the sum of squared differences (SSD) to mutual information (MI).

For the translations, the mean 3D error was found to be 0.2mm for SSD, and 0.15mm for MI. For rotations, the standard deviation of the estimation error was 0.18° for SSD, and 0.08° for MI. The results show that the proposed approach is feasible. Clinical validation studies on patient images will now be undertaken.

8856-49, Session 7

Motion estimation and segmentation in CT cardiac images using the Hermite transform and active shape models

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Considering the importance of studying the movement of certain cardiac structures such as left ventricle and myocardial wall for better medical diagnosis, we propose a method for motion estimation and image segmentation in sequential 3D Computed Tomography images. Two main tasks are tackled. The first one consists of a method to estimate the heart's motion based on a bio-inspired image representation model. Our proposal is based on the polynomial decomposition of each of the sequence images using the steered Hermite transform as a representation of the local characteristics of images from a perceptual approach within a multiresolution scheme. The Hermite transform is a model that incorporates some of the more important properties of the first stages of the human visual system, such as the overlapping Gaussian receptive fields, the Gaussian derivative model of early vision and the multi-resolution analysis. We propose an approach for optical flow estimation that incorporates image structure information extracted from the steered Hermite transform coefficients that is later used as local motion constraints in a differential estimation approach. The second task deals with cardiac structure segmentation in time series of 3D cardiac images based on deformable models. The goal is to extend active shape models (ASM) of 3D objects to the problem of 4D (3D + time) cardiac CT image modeling. The segmentation is achieved by constructing a point distribution model (PDM) that encodes the spatio-temporal variability of a training set. An active search is used in the segmentation process where an initial approximation of the spatio-temporal shape is given and the gray level information in the neighborhood of the landmarks is analyzed. The starting shape is capable of deforming so as to better fit the data, but in the range allowed by the point distribution model. Combination of both motion estimation and image segmentation allows isolating motion in cardiac structures of medical interest such as ventricle walls.

8856-50, Session 7

Midbrain volume segmentation using active shape models and LBPs

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Midbrain or mesencephalon is an approximately 2x2x1 cm sized region near the center of the brain that serves as a relay center for visual, auditory, and motor system information. Due to the fact that the most common illness associated with this region is Parkinson's disease, midbrain segmentation has become an important issue in neurological applications. Recently, Magnetic Resonance Imaging (MRI) has been used to detect different brain structures such as midbrain, white matter, grey matter, corpus callosum, and cerebellum due to the good offered resolution and the advantage to obtain different image modalities (for instance, T1 or T2 weighted modes). The first step to analyze Parkinson's disease is midbrain segmentation. So far, Active Shape Models (ASM) have been extensively used in literature for organ segmentation where the shape can be used as a discriminant feature. However, fine adjustments can be improved using Local Binary Patterns (LBP), originally proposed by Ojala. In this paper we propose a novel method based on the combined used of ASM and LBPs. The joint-model results outperform the final segmentation because it considers both global and local statistics provided by ASM and labeled LBP histograms, respectively. Furthermore, we evaluate different LBP algorithms to asses the best implementation for the midbrain segmentation. Comparatives will be done using the classical ASM approach and our different ASM+LBP schemes.

8856-51, Session 7

Real time contact-free and non-invasive tracking of the human skull: first light and initial validation

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In an increasing number of fields in medicine, precise and fast localisation of bony targets inside the body is essential. Up to now, exact localisation in the operation room can either be done with invasive methods like X-ray imaging and electromagnetic tracking systems, with volumetric ultrasound or by fixing the target in place. In this work, we present a new technology to directly track the position of the human skull through tissue in real time using infrared lasers.

To achieve this, an experimental setup has been developed to precisely target a position on a subject's skin with an 850 nm laser. The primary reflection on the skin is triangulated using a high-speed camera. Additionally, the reflections as well as in-tissue scattering are recorded with an in-beam setup of a NIR sensitive high-speed and high-resolution camera. Consequently, it is possible to record the scattering patterns specific to the composition of the tissue at the target.

We have recorded MRI data of three test subjects (voxel size 0.15 x 0.15 x 1mm?) and extracted the soft tissue thickness with a semi-automatic segmentation approach. The MRI data was validated using force-controlled 2D ultrasound (tracked by an optical tracking system), from which soft tissue thickness was segmented manually. Optical measurements and MRI data were registered to determine soft tissue thickness for each measured laser target and finally used to train a support vector regression machine.

Using the optical setup, we succeeded in computing the soft tissue thickness on the subjects' foreheads with sub-millimetre accuracy.

8856-52, Session 7

Optical system to compute intensity moments for gait description

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A hybrid optical-digital processor for gait description is presented. The processor computes invariant moments of an image by spatial convolution with a single mask. The invariant moments are independent of shift and rotation. An invariant moment history (MH) is obtained from N-frames to describe the history shape of individuals. The feature gait

extraction for each subject is a difficult problem because the starting point of the gait cycles or MH is different for the same subject. Also, the same subject do not walk at the same way in each sample, thus will be required to choose the better sequences which can be set on phase. A method to calculate the temporal correlation in terms of a moment function representation of lower body images for gait recognition is presented. The starting point of the gait cycles is solving through Genetic Algorithms. Descriptors are obtained by selected MHs in phase. By using the combined metrics of correlation and minimum distance classifier M-classes, fitting only the selected features in order to obtain the highest Correct Classification Rate (CCR). The databases used here are MoBo, CASIA A, and our home database. In general, we see that the proposed algorithm has good performance in the three databases.

8856-53, Session 7

3D surface reconstruction based on image stitching from gastric endoscopic video sequence

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Gastric endoscope is a very essential tool used for examining any gastric abnormalities or growths. It is a flexible fiber-optic scope with a light that helps a physician see inside certain internal organs. However, gastric endoscopy can only provide a narrow view angle and 2D structures of the internal organs. In order to expand the view angle and describe the details of 3D organ structures, we propose an approach to reconstruct 3D gastric surface based on image stitching from an endoscopic video sequence.

The proposed method consists of the following three steps: (1) 3D reconstruction, (2) 3D point cloud stitching and (3) dense point cloud creation. In the beginning, we separate one video sequence into image groups, each of which consists of two frames, where subsequent two groups share one overlapping frame as stitching region. Then, in (1), the 3D point cloud of each group is reconstructed by utilizing structure from motion (SFM). Next, in (2), SIFT feature based algorithm registers and stitches the 3D point clouds obtained in (1), by estimating the transformation matrix of the overlapping frame (stitching region) in the two subsequent groups with a high accuracy and efficiency. Finally, in (3), we select the most robust SIFT feature points as the seed points, and then obtain the dense point cloud from sparse point cloud through a depth testing method presented by Furukawa. Consequently, dense points, threefold in size, in all the groups are combined together so that the entire 3D gastric structures are obtained.

Experimental results demonstrate that the proposed method achieves a satisfied accuracy and efficiency for the 3D reconstruction of gastric surface from an endoscopic video sequence, and promise a large view angle.

8856-63, Session PWed

Combination of graph theoretic grouping and time-frequency analysis for image segmentation with an example for EDI-OCT

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We introduce a nonparametric approach to multiscale segmentation of images using a hierarchical matrix analysis framework called diffusion wavelets that tries to benefit from the advantages of both graph theory and wavelet transform. Till now a broad range of multiscale transforms like wavelets (and other x-lets) have been introduced for image segmentation task. Furthermore, graph theoretic formulation of grouping is also well-known to deal with this problem. The combination of multiscale transforms and graph based partitioning results in a scale-spectral method exploring through different scales of the image, over a great deal of spectral methods in graph partitioning. The method constructs multiscale basis functions and a series of dilation and orthogonalizations build a hierarchy, automatically. At each level, a set of basis functions is build by applying dyadic powers of a diffusion operator on the basis at the lower level. Two approaches are proposed for multiscale segmentation of images using diffusion wavelets. The first method is based on extended basis functions at each level and designing a competition between the basis value for partitioning. The second approach is defining a new distance for each level and clustering based on such distances. An example of application in Enhanced Depth Imaging Optical Coherence Tomography (EDI-OCT) is shown in this paper. The retinal structure containing inner, outer and choroidal layers of retina are segmented apart from the background by applying diffusion wavelet in a scale that produces 3 clusters.

8856-64, Session PWed

Real-time detection of respiration rate with non-contact mode based on low-end imaging equipment

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Standard instrumentation for the assessment of respiration rate is large and based on invasive method, and not suitable for daily inspection. An optical, simple and non-contact measurement method to detect human respiration rate using low-end imaging equipment is discussed. This technology is based on the visible light absorption of blood, which contains many important physiological information of the cardiovascular system. The light absorption of facial area can be indirectly reflected to gray value of the corresponding area image. In this paper, we acquire the respiration rate though the video signal captured by low-end imaging equipment. Firstly, the color CCD captures the facial area below the eyes and every frame of the video can be separated into three RGB channels. The blue channel is extracted as the research object. Then, we calculate the mean gray value for each image and draw the mean gray curve along the time. Fourier transform can get the frequency spectrogram of the graph, which is filtered through the Fourier filter. The extreme point is the value of the respiratory rate. Finally, an available interface program is designed and we have some volunteers tested. The correlation coefficient between the experimental data and the data provided by a reference instrument is 0.98. The consistency of the experimental results is very well. This technology costs so low that it will be widely used in medical and daily respiration rate measurement.

8856-65, Session PWed

Fractal evaluation of drug amorphicity from optical and scanning electron microscope images

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The assessment chemical, structural, energetic, and physical aspects of pharmaceutical compounds have to be done since the preformulation stage. Amorphous materials are metastable, and more reactive than crystalline. Detection, quantification and characterization of amorphous content given by random supramolecular arrangement are analyzed in this paper. Amorphicity is interpreted as a spatial chaos and fractal geometry is used to study patterns of molecular aggregates on solid micron-sized structures. Eleven images of dexamethasone were taken, 3 from an optical microscope, OM, enlarging from 40 to 1000, and 8 from a scanning electron microscope, SEM, which magnifies between 600 and 80000, all of them having the same resolution. At each scale, black and white images were generated by using a variable threshold in the range 0-255. The magnification and threshold influences of fractal dimension, FD, were investigated. 200 layers of grids of decreasing boxes were put over the images at each scale and threshold, and counted how

many boxes in each grid were black, white or black and white. FD corresponds to the slope of the logarithmic regression line for number of boxes and their dimension. The average FD for pattern irregularities of OM images was 1.538, and about 1.692 for SEM images. The FDs of the two kinds of boxes: black and white are less sensitive of threshold. 3D images were shown to illustrate dependence of FD of threshold and magnification level. As a result, the OM image at a single scale is enough to characterize the drug amorphicity.

8856-66, Session PWed

Automatic detection of micro-aneurysms in retinal images based on curvelet transform and morphological operations

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Diabetic retinopathy (DR) is one of the major complications of diabetes and Micro-aneurysms (MAs) are one of the first pathologies associated with DR. The number and the location of MAs are very important in grading of DR. In this paper we use Fundus Fluorescin Angiography (FFA) for extracting MAs. Our new method is based on curvelet transform and morphological operations. As vessels and MAs are the bright parts of FFA image, firstly vessels must be removed from FFA image. For this reason, after applying a curvelet-based contrast enhancement method on inverted FFA image, the curvelet coefficients of the match filtered response of enhanced image are obtained, then low frequency component is removed, and other coefficients are amplified. By thresholding of reconstructed image and applying length filtering, misclassified pixels are removed and vessels are extracted. After removing the extracted vessels from the FFA image, morphological operations are applied on resulted image for detecting MAs. For this reason, at first the image is dilated in order to produce an image in which MAs appear brighter than other pixels. By erosion of resulted image, the background of retina is obtained. In the next step the background is removed from dilated image, bright small regions are enhanced and finally MAs are detected by thresholding.

8856-67, Session PWed

A new approach to tunnel image acquisition using a fisheye lens camera

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Different types of information are required for improving work efficiency and safety in construction sites. Among numerous information sources, digital images have been largely used because they are easily available and include various information. However, it is difficult to obtain visual information from linear structures like tunnels using regular photogrammetric methods due to their structural characteristics. In this case, some studies on using linescan cameras or laser scanners have already introduced.

In this research, we proposed a tunnel image acquisition method using a fisheye lens, which is a type of super-wide-angle lens. A fisheye image covers the whole hemispherical field of tunnel in front of the camera through the wide angle of the lens. We took pictures of a tunnel using a fisheye lens camera along the moving direction. Then the cylindrical projection transformation was applied to them for producing rectangular images. Also, we analyzed the distortions generated by the characteristics of the lens and the transformation process, and a calibration equation was derived by mathematical models according to types of distortions. We implemented this approach in a program using Visual C++. Thus, tunnel mosaic images were constructed using fisheye images of actual tunnels based on this program, the condition of tunnel walls can be monitored through these mosaic images. Although the proposed method shows some degrees of uncertainty about calibrating distortions and is limited by the moderately low resolution in images, it could be applicable in terms of reducing working hours in-site monitoring and requiring relatively low cost.

8856-68, Session PWed

Scale-selective wavelet analysis of polarization images of biological polycrystalline net

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The optical model of polycrystalline networks of myocardium protein fibrils is presented. The technique of determining the coordinate distribution of polarization azimuth of the points of laser images of myocardium histological sections is suggested. The results of investigating the interrelation between the values of statistical (statistical moments of the 1st-4th order) parameters are presented which characterize distributions of wavelet-coefficients polarization maps of myocardium layers and death reasons.

8856-69, Session PWed

Stokes polarimetry of the biological tissues laser imaging Fourier spectrum in the diagnosis of oncological changes

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This paper presents a data on the method of coordinate distributions determining of Stokes vector laser images parameters of biological tissue in the frequency Fourier plane. Courtesy description of the experimental setup - Fourier stokespolarimetr of biological tissues and fluids. The optical model of polycrystalline networks of histological sections of rectum wall is suggested. The results of investigating the interrelation between the values of statistical (statistical moments of the 1st-4th order) parameters are presented. They characterize the coordinate distributions of the fourth parameter of Stokes vector of Fourier transforms of laser images of rectum wall histological sections and oncological changes. The diagnostic criteria of rectum cancer are determined.

8856-70, Session PWed

A complex noise reduction method for improving visualization of SD-OCT skin biomedical images

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In this paper we consider the original method of solving noise reduction problem for visualization's quality improvement of SD-OCT skin and tumors biomedical images. The principal advantages of OCT are high resolution and possibility of in vivo analysis. We propose a two-step algorithm: 1) process of raw one-dimensional A-scans of SD-OCT and 2) remove a noise from the resulting B(C)-scans. The general mathematical methods of SD-OCT are unstable: if the noise of the CCD is 1.6% of the dynamic range then result distortions are already 25-40% of the dynamic range. We use at the first stage a resampling of A-scans and simple linear filters to reduce the amount of data and remove the noise of the

CCD camera. The efficiency, improving productivity and conservation of the axial resolution when using this approach are showed. At the second stage we use an effective algorithms based on Discrete Wavelet Transform and Hilbert-Huang Transform for more accurately noise peaks removal. The effectiveness of the proposed approach for visualization of malignant and benign skin tumors (melanoma, BCC etc.) and a significant improvement of SNR level for different methods of noise reduction are showed. Also in this study we consider a modification of this method depending of a specific hardware and software features of used OCT setup. The basic version does not require any hardware modifications of existing equipment. The effectiveness of proposed method for 3D visualization of tissues can simplify medical diagnosis in oncology. Effective ways to implement a parallel version for high performance systems was considered.

8856-71, Session PWed

An effective method of image registration for super-resolution

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Super-Resolution is an image enhancement technique that generates a high-resolution image from several low-resolution observations, whose goal is to increase the details of image, and thus we can obtain better visual effect. Super-Resolution is most commonly used in remote sensing, medical imaging, surveillance video and video standard conversion. During the imaging acquisition process, the sub-pixel shifts between the low-resolution images can produce non-redundant information. The basic idea behind Super-Resolution is to extract the non-redundant information from several low-resolution images and further combine them. According to the reconstruction-based method of Super-Resolution, the process of it mainly contains two parts including image registration and high-resolution image estimation. At present, many appropriate image registration and estimation methods exist in different situations and accurate estimation of both parts can benefit each other. However, some image registration methods are only accuracy for small-angle estimation, not for large-angle approximation. In addition, some high-resolution image estimation methods are easier to incorporate constraints and priors, but which have the disadvantages of heavy computation and slow convergence. Based on the current mainstream methods, an effective method of super-resolution imaging reconstruction is proposed in the paper. The proposed method is a better combination of present methods, which also takes into account the registration precision and the computation efficiency. The experimental results demonstrate that the proposed method is effective in the imaging reconstruction using the simulation and real test images.

8856-72, Session PWed

Evaluation of different classifiers for palmprint based personal identification

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The ever increasing demand of security has resulted in wide use of Biometric systems. Palmprint based personal verification is an accepted biometric modality due to its reliability, ease of acquisition and user acceptance. This paper presents a novel palmprint based identification approach which draws on the textural information available on the palmprint by employing Non Sub Sampled Contourlet Transform. Center of the palm is calculated using the Distance Transform and by calculating the parameters for the best fitting ellipse, the alignment of hand θ is found. Rotational invariance is achieved by cropping a square region of size 256 x 256 pixels around the center aligned at θ degrees. After establishing the region of interest (ROI), the two dimensional (2-D) spectrums is divided into fine slices, using iterated directional filter banks. Next, directional energy components for each block of the ecomposed subband outputs are computed. The proposed algorithm captures global details in a palmprint as fixed length palm codes. Palmprint matching is then performed using Normalized Euclidean Distance Classifier, Support Vector Machine and Baysian Classifier. Subject methods are tested on a total of 500 palm images of GPDS Hand database, acquired from University of Las Palmas de Gran Canaria, Spain. The experimental results were compiled for individual classifiers. The use of different classifiers demonstrated their strength and feasibility in application to palmprint biometric modality. The results from Support Vector Machine shows the best results by exhibiting Genuine Acceptance rate of 99.2%, Decidability Index of 2.7782 and Equal Error rate of 0.4133%.

8856-73, Session PWed

A novel method for detection of preferred retinal locus (PRL) through simple image processing using MATLAB

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Although there are various methods like micro perimeter, Scanning Laser Ophthalmoscope (SLO) available in detecting 'Preferred Retinal Locus' (PRL), a simple and new technique has been proposed in this paper. The technique uses simple MATLAB algorithms in detecting the RGB color pixel intensity values of normal retinal images and images with central scotomas. This technique proved non-existence of 'S' cones in Fovea Centralis and also proposes rods are involved in blue color perception. Similarly, the average photoreceptor cells ratio has also been studied. Retinal images of central vision loss and normal retina were taken for image processing. Blue minimum, Red maximum and Red+Green maximum were the three methods used in detecting PRL. All three methods spotted the same location of the PRL. Comparative analyses were also performed for these methods with patient's visual acuity and visual fields. Preliminary studies show promising results for the proposed method in terms of reliability and repeatability.

8856-74, Session PWed

Real-time 3D imaging by using color structured light based on Hilbert transform

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A method for real-time three-dimensional (3D) reconstruction based on Hilbert transform is proposed. Based on the properties of Hilbert transform and De Bruijn sequence, we design an encoding technique based on color fringe patterns to realize 3D reconstruction of the phase distribution and range images. The calculation of phase map is implemented by using two sinusoidal fringe patterns with phase shifting 0 and pi/2 each other. Two phase-shifted fringe patterns are assigned to the red and blue channel of a color pattern, respectively. After color calibration of the captured color pattern picture having been done, the phase unwrapping is accomplished with aid of the De Bruijn sequence pattern stored in the green channel. With the parameters of a pre-calibrated 3D imaging system consisting of a cameral and a projector, we can calculate the 3D range data of the object. A spoon has been measured by this method. The experiment results show that the proposed method can not only acquire 3D data in real-time and one-shot fashion, but also obtain high-resolution and high-density range image data without any error propagations.

8856-75, Session PWed

Image reconstruction in speckle interferometry

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Speckle imaging technique is one of the several effective methods, which can overcome atmosphere turbulence effects and obtain diffraction-limited resolution of objects. It is achieved by the integration of a series of short-exposure images of the object.

This paper is the part of a series dedicated to the speckle imaging of binary stars carried out by the research team of Shanghai Astronomical Observatory. The observation experiments were carried out from 2010 to 2012 with 1.56-m telescope using a speckle camera, and the high resolution image were reconstructed successfully.

In this paper, we mainly concerned speckle interferometry and iterative shift-and-add. Speckle interferometry was proposed by Labeyrie in 1970, the information obtained in this manner is not easily interpreted because the final output after processing is the autocorrelation of the object. This technique has been widely used in the observational astronomy, especially in binary stars. Iterative Shift-and-Add is working in spatial domain, the complex Fourier phase recover is avoided in this method and the data processing become much easier.

As we know, speckle imaging algorithm needs to deal thousands of images, and the high computational complexity brings a lot of problems. Modern GPUs are very efficient at manipulating computer graphics, and their highly parallel structure makes them more effective than general-purpose CPUs for algorithms where processing of large blocks of data is done in parallel. So we proposed a reconstruction software based on CUDA architecture, compared with C++ program based on CPU, the speed ratio can reach 10 times.

8856-76, Session PWed

Modeling of quantization noise in linear analog-to-digital converter

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Quantization noise is present in all the current digital imaging systems, therefore its understanding and modeling is crucial for optimization of image reconstruction techniques. Hence, this paper deals with modeling of the quantization noise. We exploit the undecimated wavelet transform (UDWT) for signal representation. We assume that the quantization noise in the spatial domain can be seen as additive, white and uniformly distributed. Hence, the UDWT causes the transform of noise distribution due to weighted sum of noise samples and filter coefficients. From the known quantization step we are able to estimate suitable moments of noise uniform probability density function (PDF). These moments then could be directly evaluated in the undecimated wavelet domain using the derived equations. The presented algorithm gives the a priori information about the quantization noise and can be used for the suppression of it.

8856-77, Session PWed

A comparison between x-lets in denoising cDNA microarray images

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Microarray technology has become a power tool in the field of bioinformatics. It is used to measure gene expression levels which similar to any other image capturing processes is prone to noise. There are different kind of noise, during preparation, hybridization and scanning in microarray images. In the literature, the noise is usually modeled by a Gaussian and Poisson probability density function (pdf), but the Poisson noise can also be converted to Gaussian noise, therefore only effect of Gaussian noise is studied. Since introduction of wavelets in 1970s, many more forms of this transform have been developed and used, such as stationary wavelet transform (SWT), complex wavelet transform (CWT), curvelet transform (CURV), contourlet transform (CNT), etc. By developing of more sparse transforms, it is important to have a perspective of how efficient the transforms are in different applications, such as microarray technology. In this paper, we compare the efficiency of common sparse transforms including discrete wavelet transform (DWT), SWT, CWT, CURV, CNT, contourlet-SD decomposition, steerable pyramid (SHR) and shearlet transform (ST) using different quality indexes like peak signal-to-noise ratio (PSNR), structural similarity (SSIM) index, and edge preservation index (EPI). For this reason after converting microarray image into x-let transform, BayesShrink method and soft thresholding is used to perform denoising of these images. Both local and general thresholds are calculated for each subband in order to evaluate the effect of incorporating intrascale dependency on top of sparsity property in statistical modeling of x-let's coefficients. Our simulation results show that CWT and SHR outperforms the others. Although SHR has better performance for some criteria like SSIM, but CWT is faster than SHR. We are now working to develop a new transform namely circlelet which has been designed based on this fact that the main objects in microarray images are circle-like objects.

8856-79, Session PWed

Development of FORMOSAT-5 automatic cloud coverage assessment method

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FORMOSAT-5 is the fourth satellite owned by National Space Organization (NSPO), National Applied Research Laboratory (NARL) of Taiwan. The primary payload of FORMOSAT-5 is a high-spatial-resolution (2meters) optical Remote Sensing Instrument (RSI). FORMOSAT-5 is currently scheduled to be launched in 2014. Specifically, FORMOSAT-5 imagery is a kind of remote sensing satellite data, which includes one panchromatic band and four multispectral bands (Blue, Green, Red, near-infrared). An essential sector in the daily processing of received FORMOSAT-5 imagery is to estimate the cloud statistic of imagery by using Automatic Cloud Coverage Assessment (ACCA) method. The information of cloud statistic of imagery is subsequently recorded as an important metadata for corresponding imagery product catalog. In this paper, our proposed ACCA method is generally divided into two consecutive stages: pre-processing and post-processing analysis for the cloud statistic estimation and results examination, respectively. For pre-processing analysis, the un-supervised K-means classification, edge-detection method, thresholding method, and non-cloudy pixels reexamination are implemented in sequence. A simulated FORMOSAT-5 imagery with a broad range of different kind of scene features is used for validation. The research supports that the use of our proposed ACCA method as a reliable approach for the cloud statistic estimation of the FORMOSAT-5 imagery.

8856-80, Session PWed

Polarization mapping temporal changes of the eye optical anisotropy laser images necrotic changes in the diagnosis of biological tissues

Taras Boychuk, Darina Popovych, Bukovinian State Medical Univ. (Ukraine)

This research is focused on the study of potentiality of laser mapping of polarization azimuths and ellipticity distribution of eye vitreous body laser images with the aim to define the prescription of death coming.

The research was carried out at the conventional setup of laser polarimeter. By turning the analyzer axis at an angle within 00 – 1800 the arrays of minimal and maximal intensity levels of biological tissue image were determined for every pixel of CCD-camera, as well as the rotation angles corresponding to them. Further, the coordinate distributions (polarization maps) of polarization azimuths of a biological object were calculated.

The statistic structure of coordinate distributions of ellipticities of an image of biological tissue histological section is most objectively characterized by the ensemble of statistical moments 1st – 4th orders. As objects of investigation the histological sections of human eye vitreous body tissue were used, taken in 4 hours and 72 hours after death coming.

The dynamics of change of random distribution of polarization ellipticity is characterized by the following difference between the values of statistical moments of the 1st -4th orders: mean ; dispersion – ; asymmetry – ; excess – . It is obvious that the values of all statistical moments, as well as those of polarization azimuth distributions, change manifold within one order of a value with the increase of time after death coming.

The statistical moments of 3rd -4th orders of values distributions of polarization azimuths and ellipticity of the laser object field of human eye vitreous body tissue appeared to be the most informative.

8856-81, Session PWed

Fourier analysis of blood plasma laser images phase maps in the diagnosis of cancer in human organs

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The main idea of such an approach lies in the fact that spatial-frequency structure of the Fourier form of the laser image of the polycrystalline network of blood plasma is different for its large scale albumin and small scale protein structures. Therefore, through space-frequency filtering one can mainly select either low-frequency (with linear birefringence) or high-frequency (with circular birefringence) components which by means of reverse Fourier transformation can be converted into corresponding “separated” laser images.

A model of the polycrystalline networks optical anisotropy of blood plasma has been suggested and the method of Fourier phasometry of linear parameters (a phase shift between the orthogonal components of the laser wave amplitude) and circular (the angle of rotation of the polarization plane) birefringence with a spatial-frequency selection of the coordinate distributions for the differentiation of acute and gangrenous conditions have been analytically substantiated.

Comparative studies of the efficacy of the methods of direct mapping of phase distributions and Fourier’s phasometry of a laser radiation field transformed by the dendritic and spherulitic networks of albumin and globulin of the layers of breast and colon effusion on the basis of statistical analysis of the structure of phase maps.

A set of criteria of a polarization-phase differentiation of normal and cancer states has been detected and substantiated: statistical moments of the 1st - 4th order, which characterize the distribution plane relations of polarization laser radiation stipulated by circular birefringence of blood plasma network.

8856-82, Session PWed

2D reconstruction of biological tissues polycrystalline structure by analyzing Mueller-matrix singular images

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In this work, we have theoretically grounded conceptions of characteristics points observed in coordinate distributions of Mueller matrix elements for a network of human tissue biological crystals. Found is interrelation between polarization singularities of laser images inherent to these biological crystals and characteristic values of above matrix elements.

As objects for our experimental investigations, we used mounts of myometrium tissue of two types:

• biopsy of healthy tissue from a woman matrix (type A);

• biopsy of conditionally normal tissue from the vicinity of a benign hysteromyoma (type B).

We have determined criteria for statistical diagnostics of pathological changes in the birefringent structure of biological crystal network by using myometrium tissue as an example.

- values of the skewness coefficient for distributions of Mueller matrix images (MMI) characteristic values describing the pathologically changed myometrium tissue of B type grow practically by one order, which indicates formation of their azimuthal asymmetry related with the direction of pathological growth of birefringent protein fibrils.

Thus, the above analysis of statistical distributions describing the number of points for MMI characteristic values inherent to the set of matrix elements characterizing biological tissues of different kinds seems to be efficient in differentiation of phase and orientation changes in the structure of their birefringent components, which are related with changes in their physiological state.

8856-83, Session PWed

Singular structure of Mueller matrices images of biological crystal networks for diagnostic human tissues pathological changes

Volodimir G. Ushenko, Mikhailo Sakhnovskiy, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

The interconnection between geometry of organic crystal structure with their polarization properties has been studied. It has been shown that for physiologically normal biological tissues polarization properties of radiation scattered on architectonic nets formed by protein fibrils possess the fractal character. Pathological changes of organic crystal architectonics are accompanied with the transformation of singular structure of Mueller-matrix images.

It has been demonstrated that self-similar geometric structure of architectonic nets of physiologically normal organic crystal of various morphology manifests itself in the singular character of their polarization properties, described by the totality of 2D elements of Mueller matrices. The processes of pathological changes of organic crystal architectonics manifest themselves in the appearance of new inclinations and the transformation of the structure of Mueller – matrixes images orientation elements into a stochastic one and by the transformation of large-scale structure of Mueller – matrixes images phase elements into a statistic one. Degenerative-dystrophic changes manifest themselves in randomization of coordinate distributions of Mueller matrices of orientation elements of large-scale architectonics elements and by complete destruction of self-similar structure of Mueller – matrixes images of phase elements.

8856-84, Session PWed

Correlation and self similarity structure of polycrystalline network biological layers Mueller matrices images

Volodimir G. Ushenko, Alexander V. Dubolazov, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

The application of lasers in biomedical diagnostics gave the possibility to use the polarization analysis of different kind object fields – speckle-modulled fields, the transformation operator of which is Mueller matrix. The topological inhomogeneity of coherent fields makes it possible to get the information on such an operator's microstructure, which is inaccessible for the traditional nephelometry and is defined by the object morphology specificity.

This investigation is aimed at studying Mueller matrix microstructure of architectonics of different morphological structure organic crystals; at searching the correlation of orientation, anisotropy parameters of multifractal nets with the topological distribution of matrix elements and their indices.

The interrelation of orientation, anisotropy structure of organic crystals architectonics and topological element distribution of Mueller's matrices is investigated here. It is researched the analytical correlation of object Mueller's matrices microstructure with matrix element indices measured in the far field of Fraunhofer's diffraction. The investigation is also dealt with the computer modeling and experimental researching the structure of matrix operator of multifractal amorphous – crystalline organization of different morphological structure biotissues.

Here it has been studied the correlation Mueller's matrices microstructure of biotissues and determined the interrelation of orientation, anisotropy structure of multifractal nets of their architectonics as systems of optically uniaxial crystals with the topological distribution of matrix elements within object plane.

8856-85, Session PWed

Mueller-matrices polarization selection of two-dimensional linear and circular birefringence images

Volodimir G. Ushenko, Galina Koval, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

The polarimetric method of information polarization selection, which is effective in phase-inhomogeneous layer (PIL) diagnostics in their images has been presented. The possibilities of polarization-correlation analyses of architectonics images of the BT have been studied.

The 2-component amorphous-anisotropic model of describing optical properties of boitissues of different morphological structure was analyzed.

Based on 2-component amorphous-anisotropic model of describing optical properties of boitissues of different morphological structure the correlation structure of the images of biostructures with various types of architectonics were experimentally investigated:

texture-ordered (butterfly's wing, scale);

biotissues with fibrillar type of architectonics (bone and myocardium tissue);

biotissues with disordered architectonics (lymph and large intestine).

It was shown that geometric structure of all types of investigated bioobjects possesses either fractal or stochastic character. Observations of optical anisotropy of such objects architectonics are individual for each of them.

It was determined that inflammation processes lead to statistic character of the optica0anisotropic images structure. Degenerative-dystrophic changes are shown in destroying fractal structure of images of large-scale architectonic elements.

8856-86, Session PWed

Experimental evaluation of vergence-accommodation conflict for various stereoscopic display technologies and stereoscopic content

Tomas Jindra, Karel Fliegel, Stanislav Vitek, Milos Klima, Czech Technical Univ. in Prague (Czech Republic)

Conventional 3D stereoscopic and autostereoscopic displays suffer from conflict between vergence and accommodation. The vergence-accommodation mismatch is one of important factors potentially causing visual discomfort to viewers of stereoscopic presentations. This paper presents a study analyzing the vergence-accommodation mismatch for a group of observers based on simultaneous measurement of vergence and accommodation. Our own video based eye-tracking system was coupled with stereoscopic or autostereoscopic display while various types of stereoscopic content were presented to the viewers, including real-world and artificial stimuli. Quality of presented stereoscopic images is subjectively assessed by the observers and the subjective results are consequently compared with the measured vergence and accommodation parameters. Correlation analysis between the subjective scores and measured viewing parameters is presented. This analysis aims to answer the question on how the vergence-accommodation conflict affects quality of viewing experience for stereoscopic and autostereoscopic displays with various types of stereoscopic content. The experiment extends our previously published results where only simple stereoscopic stimuli were utilized including also natural stereoscopic content.

8856-88, Session PWed

Skin chromphore mapping by means of a modified video-microscope for skin malformation diagnosis

Amina Bekina, Uldis Rubins, Ilze Diebele, Janis Zaharans, Janis Spigulis, Univ. of Latvia (Latvia)

In this study digital video-microscope was modified for an advanced skin surface monitoring. The skin lesions were illuminated with four-color LED system – red (660 nm), green (545 nm), blue (450 nm) and infrared (940 nm). A set of four images has been obtained at each measurement. Specific values related to the R-, G- and B- bands at each pixel are selectively extracted from the image and used for multispectral analysis of the image. Additionally spectral images were calibrated with white reference (I_ref) to prevent overexposition of the skin malformation image. Spectral image intensity (I_skin) was calculated using the following formula: OD=log ((I_ref-I_noise)/I_skin-I_noise). From these stabilized images three chromophore maps are calculated: hemoglobin, erythema and melanin. Hemoglobin map can be found from the relation between two spectral images at red and green illumination. Erythema index is calculated by the deviation of two residuals: E=(I_green-I_red)/ (I_blue-I_red). Melanoma related map can be found from following formula: M=I_green/I_red/I_infrared . Wavelength 545 nm (green) corresponds to maximum absorption of blood, while at 650 nm (red) hemoglobin absorption is minimal and melanin absorption is more pronounced, and 940 nm (infrared) is the longest available wavelength corresponding to the deepest penetration under the skin surface. There are visible differences between the chromophore maps. The hemoglobin map more highlight the intradermal structures of skin while the melanin map highlight the upper pigmented tissue layers.

8856-89, Session PWed

Graphical user interface (GUIDE) and semi-automatic system for the acquisition of anaglyphs

Marco A. Canchola Chávez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Juan A. Arízaga Silva, Jose M. Cantero Nava, Eduardo Tepanecalt Castillo, Univ. Tecnológica de Puebla (Mexico)

Several studies in the area of pedagogy have shown greater acceptance by youth to ideas related to science, using various teaching techniques or experiments, compared to just the texts in the classroom. That fact and showing great curiosity, are factors to consider to undertake scientific outreach efforts for children, with prospects of success.

Moreover now 3D digital images have become a topic that has gained importance in various areas, entertainment, film and video games mainly, but also in areas such as teaching transcendental.

This paper presents a system model for 3D images for education that allows students of various grade levels, school and college, have an approach to image processing, explaining the use of filters for stereoscopic images that give brain impression of depth.

The system is based on one of two hardware elements, centered on an Arduino board, and a software based on Matlab. The paper presents the design and construction of each of the elements, also presents information on the images obtained and finally how users can interact with the device.

8856-90, Session PWed

Real time soft-partition-based weighted sum filtering using GPU implementation

Shuqun Zhang, College of Staten Island (United States)

Recently image processing such as restoration, super-resolution and noise reduction using soft-partition based weighted sum filters have shown state-of-the-art results. Partition-based weighted sum filters are spatially adaptive filtering techniques by combining vector quantization and linear finite impulse response filtering concepts, which have shown to achieve much better results than spatial-invariant filtering methods. However, they are computationally prohibitive for practical applications because of enormous computation involved in both filtering and training. Real-time processing is impossible even for small window size. In this paper present a fast implementation of soft-partition based weighted sum filters by exploiting the massively parallel processing capabilities of a GPU within a CUDA framework owing to its easy off-the-shelf availability and programmer friendliness. To our knowledge there is no GPU implementation reported for partition based weighted sum filters yet. For the implementation, we focus on memory management, system design, and implementation strategies. The performance on various window sizes is measured and compared between GPU-based and CPU-based implementations. The results indicate that GPU-based implementation can significantly accelerate computations for filtering and training, and make real-time filtering become possible. Application in image restoration is also demonstrated.

8856-91, Session PWed

Analysis of skin moles from optical spectropolarimetric images

Yitzhak Yitzhaky, Lior Graham, Ibrahim Abdulhalim, Ben-Gurion Univ. of the Negev (Israel)

Imaging of the skin to detect the signs of cancer becomes very common these days. A new noninvasive skin imaging method developed recently gives an informative image data about the skin tissue by collecting scattered polarized light reflected from a mole area. This method, called Differential Optical Spectropolarimetric Imaging (DOSI), scans the polarization states by continuously rotating a linearly polarized light incident on the lesion and collecting the reflected sequence of images with a CCD camera. The two main wavelengths that were used in the study were 520nm (penetration is about 100µm) and 700nm (penetration is about 200µm). The recorded images were taken from ten patients who came to remove various skin lesions in the Ambulatory Surgery Department of Plastic Surgery in Soroka-Hospital.

Methods developed in the past to diagnose suspicious moles were implemented to visual images. However, such methods cannot be employed directly to the DOSI images because of their different properties. For example, unlike visual images, DOSI images do not have color information. In this paper, we propose a novel method to distinguish cancerous from healthy moles by analyzing the images obtained by this new imaging system. The proposed method first pre-processes the image of the mole, which include image de-noising, intensity-based segmentation of the mole region and contour formation of the segmented regions. Then, it performs an automatic examination of the polarized images according to characteristics such as their border disorder, asymmetry, cross-image local contrasts and large-scale homogeneity. Results show good separation between cancerous and healthy moles.

8856-92, Session PWed

Autofocusing in microscopy systems using parallel computing

Jorge Alberto Hernández Tapia, Juan Carlos Valdiviezo-Navarro, Carina Toxqui Quitl, Alfonso Padilla-Vivanco, Univ. Politécnica de Tulancingo (Mexico)

Autofocusing is of fundamental importance for a real time automatic system. In particular, for microscopy applications, a desired automatic system should provide the best focused image with enough accuracy and the minimum computational time. During the last years several metrics based on images have been proposed to achieve the autofocusing process. Although many of these techniques present good accuracy in microscopy applications, their main limitations reside in the high computational time required to find the best focused image. Moreover, in recent years the development of graphical processing units (GPUs) has given place to new and diverse applications oriented to diminish the computational effort associated to the central processing unit (CPU). This manuscript presents an implementation of different autofocusing techniques, such as Vollath F4, Tenengrand, Mid-Frequency Discrete Cosine Transform, and Spatial Frequency, using tools of parallel computing. The main objective of the proposed manuscript is to show that by using a GPU is possible to speed up the computational time required to perform the above mentioned techniques. Preliminary results obtained when applying parallel computing to a stack of microscopy images have allowed us to reduce the computational effort around 12%. Hence, parallel computing can be effectively used for autofocusing in real time microscopy applications.

8856-93, Session PWed

Automatic fuzzy based level set method for segmentation of Barrett's esophagus in endoscopy images

Hossein Yousofi, Hossein Rabbani, Peyman Adibi, Isfahan Univ. of Medical Sciences (Iran, Islamic Republic of)

Evaluation of the Barrett's disease progress needs to detect the baseline; a region in endoscopy images that esophagus tissue is finished and stomach tissue started. The main purpose of this paper is segmentation of Barrett's esophagus in endoscopy images automatically using a fuzzy based level set method. Both fuzzy C-means (FCM) and level set methods fail to segment this type of medical image due to weak boundaries. This paper tries to benefit from the advantages

of both methods for segmentation of Barrett's esophagus. In image segmentation by nave level set method, contour initialization needs manual manipulation. A modified fuzzy based level set method is proposed in this paper to segment Barrett's esophagus automatically. We use FCM algorithm with spatial information to cluster image into number of clusters. By computing the correlation between obtained fuzzy clusters and a binary of original image with a proper threshold, we can define the best initial contour to serve the level set algorithm. The final segmentation is obtained from level set method that uses the sign pressure force function for controlling the contour. Results showed that this proposed method can segment Barrett's esophagus in endoscopy images effectively.

8856-94, Session PWed

The best features selection for Leukocytes classification in blood smear microscopic images

Omid Sarrafzadeh, Hossein Rabbani, Ardeshir Talebi, Isfahan Univ. of Medical Sciences (Iran, Islamic Republic of)

Automatic differential counting of leukocytes provides invaluable information to pathologist for diagnosis and treatment of many diseases. The main objective of this paper is to detect leukocytes from a blood smear microscopic image and classify them into their types: Neutrophil, Eosinophil, Basophil, Lymphocyte and Monocyte using features that pathologists consider to differentiate leukocytes. Features include color, geometric and texture features. Colors of nucleus and cytoplasm vary among the leukocytes. Lymphocytes have single, large, round or oval and Monocytes have singular convoluted shape nucleus. Nucleus of Eosinophils is divided into 2 and of Neutrophils into 2 to 5 segments. Lymphocytes often have no granules, Monocytes have tiny granules, Neutrophils have fine granules and Eosinophils have large granules in cytoplasm. We extract 6 color features from both nucleus and cytoplasm, 6 geometric features only from nucleus and 6 statistical features and 7 moment invariants features only from cytoplasm of leukocytes. The features are fed to support vector machine (SVM) classifiers with one to one architecture. The results obtained from applying the proposed method on blood smear microscopic images of 10 patients including 149 white blood cells (WBCs) indicate that correct rate for all classifiers are above 93% which is in a high level in comparison with previous literatures.

8856-95, Session PWed

Comparison of macular OCTs in right and left eyes of normal people

Tahereh Mahmudi, Raheleh Kafieh, Hossein Rabbani, Isfahan Univ. of Medical Sciences (Iran, Islamic Republic of)

Optical coherence tomography (OCT) is a non-invasive imaging modality being used in the diagnosis and management of a variety of ocular diseases including glaucoma, age-related macular degeneration (AMD) and diabetic macular edema. It is a powerful modality to qualitatively assess retinal features and pathologies or to make quantitative measurements of retinal morphology. Retinal 3D OCT volumes are commonly used for clinical diagnosis or investigation. But accurate and fast analysis of large volumes of data is difficult for clinicians. Therefore, automatic extraction of useful information from OCT images, such as calculating total retinal thickness and nerve fiber layer (NFL) thickness (RNFLT) have become increasingly significant. It is also important to have information about thickness of retinal layers in right and left eyes. If the asymmetry of RNFLT in normal eyes is not taken into consideration, a mistake could be made in evaluating whether there is damage or not. The only published study in this area by park et al. suggested that the RNFLT around Optic Nerve Head in normal eyes is not symmetrical within individual eyes nor symmetrical between the right and left eye. In this study we investigate the thickness values in two eyes in an area around the macula. Retinal borders and RNFL border were segmented by diffusion map method and thickness profiles were made. To show the result, RNFLT and retinal thickness were analyzed by dividing three circle scanning areas (diameter 1, 3, 6 mm) around the macula into 4 quadrants and 9 sectors.

8856-96, Session PWed

Automatic diagnosis of malaria by use of least square circle-ellipse fitting search

Monireh Sheikhhosseini, Isfahan Univ. of Technology (Iran, Islamic Republic of); Hossein Rabbani, Isfahan Univ. of Medical Sciences (Iran, Islamic Republic of); Maryam Zekri, Isfahan Univ. of Medical Sciences (Iran, Islamic Republic of) and Isfahan Univ. of Technology (Iran, Islamic Republic of); Ardeshir Talebi, Isfahan Univ. of Medical Sciences (Iran, Islamic Republic of)

Diagnosis of malaria parasitemia from blood smears needs enormous time and effort. Automatic diagnosis process is able to reduce the diagnosis time, also it may be useful in malaria screening. This study presents an automatic method for diagnosis malaria in thin blood smears. First step of malaria diagnosis is identifying stain objects which are colored through staining process. Infected cells are verified by applying complete searching process on smooth image which makes use of nonlinear diffusion filtering. Searching procedure is composed of circle search, least square ellipse fitting and ellipse search sections. Circle search process determines the direction and initial points for ellipse fitting algorithm, while ellipse search process completes the shape of parasite. Also, far points with high error value from fitted ellipse are removed and final ellipse parameters are modified by applying ellipse search algorithm. The method was applied on total 418 Red Blood Cells (RBCs) and our experiments show high sensitivity and specificity which are 94.74% and 97.11% respectively.

8856-97, Session PWed

Study of 3D solder-paste profilometer by dual digital fringe projection

Yi-Hua Juan, Jeng-Nan Yih, National Kaohsiung Univ. of Applied Sciences (Taiwan)

In a 3D profilometer by the fringe projection, the shadow will be produced inevitably, thus the fringes cannot be detected in the region of the shadow. In addition, a smooth surface or a metal surface produces the specular reflection, and then, no projection fringe can be recorded in the region of oversaturation on CCD. This paper reveals a proposed system for improved these defects and shows some preliminary improved 3D profiles by the proposed dual fringe projection.

To obtain the profile of sample hided in the shadow and the oversaturation, this study used the dual-projection system by two projectors. This system adopted two different directions of fringe projection and illuminates them alternately, therefore, the shadow and the oversaturation produced in their corresponding locations. Two raw 3D profiles obtained from taking the dual-projection by the four-step phase-shift. A set of algorithms used to identify the pixels of the shadow and the oversaturation, and create an error-map. According to the error-map to compensate, two 3D profiles merged into an error-reduced 3D profile. We used the solder paste as a testing sample. After comparatively analyzing the 3D images obtained by our measurement system and by a contact stylus profilometer, the result shows that our measurement system can effectively reduce the error caused by shadows and oversaturation.

8856-98, Session PWed

Scene-based non-uniformity correction algorithm for continuous monotonous scene motion based on FPGA

Honglie Xu, Qian Chen, Ning Liu, Chunhua Yang, Nanjing Univ. of Science and Technology (China)

In this paper, we focus on the real scope of application and the non-uniformity appearance of the IR imager and propose a new scene-based non-uniformity correction technology. We consider the inadequacies of other non-uniformity correction algorithms and find out that most of them are only used in lab. The scene set for these algorithms often fits themselves in most cases. In real application, the scene is mostly towards one monotonous direction and has different appearance of non-uniformity. We solve these problems by developing a new projection estimator for the registration with a criterion, and realize this technology on a hardware system. This system is fully engineered for some particular usage. We test the performance of our technology by the evaluation indexes, and demonstrate the actual effect of correcting the non-uniformity under a monotonous motion on the system. At the end of this paper, we make a conclusion and perspective of our research work.

8856-99, Session PWed

Remote sensing of liquid level measurement using Fiber Bragg grating sensor

Dipankar Sengupta, M. Sai Shankar, Vidya Jyothi Institute of Technology (India); Kamineni Srimannarayana, Pachava Vengal Rao, National Institute of Technology, Warangal (India)

The present work proposes a simple low cost sensor head design making use of FBG sensor, for the remote sensing of liquid level measurement. The sensor head consists of a lever, a buoyancy tube and an FBG. The lever is used to transfer the buoyancy force due to change in liquid level to the FBG resulting in shift in Bragg wavelength. The Flexibility of this design enables to measure the liquid level in an open or closed tank.

A class I lever of length 50mm with equal arms is used. A buoyancy tube is fixed at one end of the lever. To the other end of the lever, an FBG of 3mm length is glued. The other end of the FBG is attached to the collar of the sensor arrangement with an adjusting screw for fixing the initial lever position and to give a minimal strain to the FBG and also to avoid its bending.

The sensor head is attached to a tank. To vary the liquid level in the tank, an inlet and outlet arrangement with a suitable controller is made. As the liquid level increases, an upward force acts on the buoyancy tube resulting in transfer of this force to the FBG, fixed between the collar and the lever end.

A broadband light source, a circulator and OSA are used for illuminating and recording the spectrum. During the experiment the temperature of the liquid is maintained constant. The prototype sensor head is tested by varying the liquid level in steps of one centimeter over a total span of 13 cm, the spectral shift of the Bragg wavelength was recorded. A linear change in Bragg wavelength with level is noticed with a sensitivity of 10.7pm/mm which shows the high sensitivity of the sensor head design.

A simple low cost interrogation system was made from splicing a suitable length of a 100/140?m fiber in between two single mode optical fiber (9/125 μm) which acts a linear edge filter in included in the experimental setup. As the shift in Bragg wavelength occur the intensity of the Bragg wavelength changes linearly as a result a low cost photo detector is high enough to detect the shift in wavelength.

8856-54, Session 8

Multiview wavelet transform for digital holography coding

Ângelo Arrifano, Univ. da Beira Interior (Portugal) and Univ. de Nice Sophia Antipolis (France); Marc Antonini, Univ. de Nice Sophia Antipolis (France); Manuela Pereira, Univ. da Beira Interior (Portugal)

In this paper we present multiview analysis of digital holograms by using the wavelet transform. We were successful on the reconstruction of stereoscopic information from a single phase-shift hologram captured using a 2.2μm pixel-pitch CMOS camera in a holographic interferometer configuration. The low pixel-pitch camera allows the digitizing of holograms with a higher spatial-frequency than what has been reported in the literature, allowing the recording of macroscopic objects closer to the camera sensor.

The reconstructed information can be visualized using 3D stereo glasses. From the perceived 3D we could identify several depth cues, including the occlusion effect which has not been easy to produce from single-aperture holography. The occlusion effect is also known to be difficult to produce from stereoscopic sources.

8856-55, Session 8

Using self-similarity compensation for improving inter-layer prediction in scalable 3D holoscopic video coding

Caroline Conti, Paulo Nunes, Luís Ducla Soares, Instituto de Telecomunicações (Portugal)

Holoscopic imaging, also known as integral imaging, has been recently attracting the attention of the research community, as a promising glassless 3D technology due to its ability to create a more realistic depth illusion than the current stereoscopic or multiview solutions. However, in order to gradually introduce this technology into the consumer market and to efficiently deliver 3D holoscopic content to end-users, backward compatibility with legacy displays is essential. Consequently, to enable 3D holoscopic content to be delivered and presented on legacy displays, a display scalable 3D holoscopic coding approach is required.

Hence, this paper presents a display scalable architecture for 3D holoscopic video coding with a three-layer approach, where each layer represents a different level of display scalability: Layer 0 - a single 2D view; Layer 1 - 3D stereo or multiview; and Layer 2 - the full 3D holoscopic content. In this context, a prediction method is proposed combining inter-layer prediction, aiming to exploit the existing redundancy between the multiview and the 3D holoscopic layers, and self-similarity compensated prediction (previously proposed by the authors for non-scalable 3D holoscopic video coding), aiming to exploit the spatial redundancy inherent to the 3D holoscopic enhancement layer.

Preliminary results strongly indicate that the proposed prediction method can improve significantly the rate-distortion performance of scalable 3D holoscopic video coding with respect to the authors' previous proposed solution, where only inter-layer prediction is used.

8856-56, Session 8

Wavelet coding of off-axis holographic images

David Blinder, Vrije Univ Brussel (Belgium) and iMinds (Belgium); Tim Bruylants, Vrije Univ. Brussel (Belgium) and iMinds (Belgium); Erik Stijns, Vrije Univ Brussel (Belgium); Heidi Ottevaere, Vrije Univ. Brussel (Belgium); Peter Schelkens, Vrije Univ. Brussel (Belgium) and iMinds (Belgium)

No Abstract Available

8856-57, Session 8

Compression of computer generated phase-shifting hologram sequences

Yafei Xing, Béatrice Pesquet-Popescu, Frederic Dufaux, Telecom ParisTech (France)

In this paper, an algorithm for compressing the computer generated phase-shifting hologram (CGPSH) sequences is presented to reduce the storage burden of digital holograms. By simulating phase-shifting digital holography (PSDH) interferometry, interference patterns between illuminated three dimensional(3D) virtual objects and the stepwise phase changed reference wave are generated as holograms in computer. The hologram sequences obtained by the movement of the virtual objects are compressed by a coding technique, e.g.,H.264/AVC, and a new representation method using the movement information of the objects are applied, respectively, the effectivenesses are compared as well.

8856-58, Session 8

Wavelet compression of digital holograms

Patrick Gioia, Orange Labs. (France); Kartki Viswanathan, France Telecom R&D (France)

No Abstract Available

8856-59, Session 9

Extensions under development for the HEVC standard

Gary J. Sullivan, Microsoft Corp. (United States)

This paper will review the status of standardization work on extensions of the emerging HEVC standard, including embedded bitstream scalability, 3D video, higher-quality chroma formats, extended bit depth support, and supplemental enhancement information.

8856-60, Session 9

3DTV to the home: what have we learned?

Walter J. Husak, Dolby Labs., Inc. (United States); Alexandros Mic Tourapis, Apple Inc. (United States)

This paper will be an overview of 3D ranging from theatrical releases to broadcast content. The paper will address the successes and failures and suggest what a system for the future will look like.

8856-61, Session 9

Practical operational points of multi-resolution frame compatible (MFC) stereo coding

Taoran Lu, Hariharan Ganapathy, Gopi Lakshminarayanan, Tao Chen, Peng Yin, David Brooks, Walter J. Husak, Dolby Labs., Inc. (United States)

This paper will present the results of a series of tests for broadcasters to set preferred operational points for MFC. These results will be based on a variety of content obtained from broadcasters and studios to show real world applications.

8856-62, Session 9

HEVC real-time decoding

Benjamin Bross, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); Mauricio Alvarez-Mesa, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany) and Technische Univ. Berlin (Germany); Valeri George, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); Chi Ching Chi, Ben Juurlink, Technische Univ. Berlin (Germany); Thomas Schierl, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

No Abstract Available

8856-100, Session 9

PEViD: privacy evaluation video dataset

Pavel Korshunov, Touradj Ebrahimi, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Visual privacy protection, i.e., obfuscation of personal visual information in video surveillance is an important and increasingly popular topic. However, while many datasets are available for testing performance of various video analytics, little to nothing exists for evaluation of visual privacy tools.

Since surveillance and privacy protection have contradictory objectives, the design principles of corresponding evaluation datasets should differ too. In this paper, we outline principles that need to be considered when building a dataset for privacy evaluation and present a new, and the first to our knowledge, public privacy evaluation video dataset (PEViD). This dataset can be used to evaluate a variety of privacy protection tools by either objective metrics or subjective tests.

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8857-1, Session 1

Object detection via fast discrete Curvelet transform

Hector Valdez, California State Univ. (United States); Thomas T. Lu, Tien-Hsin Chao, Jet Propulsion Lab. (United States)

Object detection is of great interest in the field of intelligent computer vision. The premise of intelligent computer vision is the hope of one day mimicking the full capability of the human visual pathway. This paper describes an automated object detection framework that is capable of processing images quickly with the primary goal of tracking objects of interest over time. We accomplish this task by means of the Fast Discrete Curvelet Transform (FDCT), which is relatively new in the subject of harmonic analysis. The distinguishing difference between FDCT and other transforms is that the curvelet coefficients have three beneficial parameters which define scale, orientation, and spatial locations. We utilize these parameters to our advantage in order to efficiently detect relatively small objects in a variety of image/video data sets. We have implemented the FDCT in the first stage of target detection in a multi-stage automated target recognition architecture. The results of the current algorithm yield a highly sensitive detection of small targets in noisy background. We will give a brief analysis of the curvelet transform, discuss the framework of the FDCT object detection stage and analyze the experimental results.

8857-2, Session 1

Iteratively compensating for multiple scattering in SAR imaging

Alejandro F. Martinez, Zhijun G. Qiao, The Univ. of Texas-Pan American (United States)

The Born approximation is a common approximation taken in modeling the physics of SAR imaging. In essence it says that radiation only scatters once when in space. This is a reasonable assumption for targets that lie far apart or that are far from the transmit and receive antennas, but it introduces error into the imaging process.

The goal of this paper is to iteratively compensate for this error in the model by using estimates of the target distribution to estimate multiple scattering phenomena. We will use a wavelet based noise reduction technique at each iteration on the corrected data as well as the estimated image to control any excess error introduced by the estimated multiple scattering phenomena. The physical model for our work will be based on the wave equation. We will briefly derive the important features of the model as well as account for the error introduced by common approximations that are made. Typically one does not get an image that is approximately the target distribution, but rather an image that is approximately proportional to the target distribution. This means that there is a scaling parameter that must be chosen when using target distribution estimates to correct data. We will discuss methods for choosing this parameter. We will provide a few basic SAR imaging methods and perform simulation using the Gotcha Data set in combination with the iterative technique. At the end of the paper we will discuss future work involving this method.

8857-3, Session 1

An examination of the application of coherent and space time adaptive processing for the detection of maritime surface targets from high altitude airborne platforms

Michael K. McDonald, Defence Research and Development Canada, Ottawa (Canada); Delphine Cerutti-Maori, Fraunhofer FHR (Germany)

Airborne wide area, maritime surface surveillance is traditionally undertaken using non-coherent, high bandwidth, radar systems operating from low altitude aircraft at low grazing angles. The planned migration by numerous countries of maritime surveillance activities to high altitude platforms, such as HALE/MALE UAVs, will result in operational performance shortfalls as non-coherent approaches will fail to detect small targets due to the order of magnitude increases in sea clutter radar cross section associated with high grazing angle geometries. This paper examines the application of coherent and Space Time Adaptive Processing (STAP) techniques to FHR PAMIR, multi-channel, medium grazing angle, real radar sea clutter data and the ability of these techniques to mitigate aforementioned performance deficiencies. Application of coherent approaches to maritime surveillance is significantly complicated by non-stationarity of sea clutter and rapid variations of clutter spectrums due to transient wave activity. The observed performance gains from maritime STAP are much more limited than those observed for Ground Moving Target Indication (GMTI) due to the inherent spectral width of sea clutter and the slow Doppler velocities of maritime targets. The impact of clutter non-stationarity across the background samples used to form the sample clutter covariance matrix is also examined. The performance of four sub-optimal STAP processing algorithms is examined and the performance differences quantified and explained in terms of the unique characteristics of sea clutter's inherent rank and spectral variability. The preferred suboptimal approach is identified and shown to provide a more practical real world implementation than theoretically ideal fully adaptive STAP.

8857-4, Session 1

Infrared small target detection technology based on OpenCV

Lei Liu, Zhijian Huang, Jilu Chen, Nanjing Univ. of Science and Technology (China)

With the continuous development of science and technology, infrared imaging technology has played an important role in national defense, medical, transportation and other areas. The detecting technology of small infrared target is an important branch of infrared imaging technology, which has not only very important scientific research value, but also has broad application prospect in the military and civil area.

Nowadays, different algorithms have been proposed for infrared target detection. However, under complex backgrounds, such as clutter, varying illumination, and occlusion, the traditional detection method often loses the real infrared small target.

To cope with these problems, firstly we have proposed four infrared target detection algorithms to enhance the detection performance according to the characteristics of the small target in infrared images, namely, traditional two-frame difference method, improved three-frame difference method, background estimation and frame differential fusion method, and building background with neighborhood mean method. Secondly, infrared small target detecting software is developed by a human-computer interaction interface created by MFC in VC++ combined with many functions in OpenCV so as to realize these four detecting algorithms. Lastly, a performance assessment conclusion is

made by analyzing the experiment results. The experimental results show that, compared with the traditional algorithm, the presented method greatly improves the accuracy and effectiveness of infrared target detection under complex scenes, and the results are satisfactory. It is of great significance for actual application of small infrared target detecting technology.

8857-5, Session 1

Improving variance estimation ratio score calculation for slow moving point targets detection in infrared imagery sequences

Revital Huber-Shalem, Ofer Hadar, Stanley R. Rotman, Merav Huber-Lerner, Ben-Gurion Univ. of the Negev (Israel)

Infrared (IR) imagery sequences are commonly used for detecting moving targets in the presence of evolving cloud clutter or background noise. This research concentrates on slow moving point targets that are less than one pixel in size, such as aircraft at long ranges from a sensor.

The target detection performance is measured via the variance estimation ratio score (VERS), which essentially calculates the pixel scores of the sequences. VERS uses two parameters – long and short term windows, which were predetermined individually for each movie, depending on the target velocity and on the clouds intensity and amount, as opposed to clear sky (noise), in the background. In this work, we examine the correlation between the sequences' spatial and temporal features and these two windows. In addition, we modify VERS calculation, to enhance target detection and decrease cloud-edge scores and false detection.

We conclude this work by evaluating VERS as a detection measure, using these two modifications. The test sequences are both original real IR sequences as well as their relative compressed sequences using the temporal DCT quantization method.

8857-6, Session 1

Identification of Human Motion Signature using Airborne Radar Data

Michael K. McDonald, Anthony Damini, Defence Research and Development Canada, Ottawa (Canada)

Data containing the radar signatures of moving persons on the ground, also known as dismounted targets, were collected at a range of 30 km from a moving airborne platform using the DRDC Ottawa X-band Wideband Experimental Airborne Radar (XWEAR). The dismounted target radar echo returns were found to possess a characteristic amplitude and frequency modulated signature which could be usefully characterised in terms parameters corresponding to the mean Doppler of the target, amplitude modulation (AM) index, frequency modulation (FM) index, FM frequency, AM frequency and the phase shift between the modulation frequencies. Examination of detection performance after space time adaptive processing revealed that performance is limited by false alarms corresponding to clutter discretes arising from large radar cross-section scatterers which are not effectively canceled during the whitening step. The clutter discretes are observed to possess different modulation characteristics from the dismount targets discussed above and the ability of pattern classification techniques to use this parameter measurement space to distinguish between dismounted targets and clutter discretes is explored and preliminary results presented. The requirement for wide area surveillance with frequent revisit and refresh of detection contacts is in conflict with the desire to use long dwells on the targets to obtain accurate parameter estimates. To this end an examination is made of the ability to extract sufficiently accurate measurements of the corresponding characteristic parameters for dismounts and clutter discretes while the radar is operated in a mode consistent with wide area surveillance.

8857-7, Session 1

Method for measuring the parameters of surface by analyzing the pulse shape of the second harmonic of laser radiation

Rustam Rysov, Vadym M. Prokopets, National Taras Shevchenko Univ. of Kyiv (Ukraine)

Investigation the parameters of solid surfaces by registering generated second harmonic of the laser radiation is very informative method. These data may help to determine the symmetry elements of the surface structure or thin film like the charge of surface or interface states, the energy spectrum of surface electrons roughness, etc. Using pulsed laser sources in optical researches allows to investigate the properties of substances for which long-term impact of intense radiation can result to destruction of the structure of matter.

Our complex was made for precise and fast registration of short light pulses from a low repeat rate for further processing.

It was developed software and hardware complex for registration first and second harmonic of laser radiation and transfering data to a computer via USB.

Wide bandwidth and differential structure of the device allows user to change the input dynamic range and offset. The hardware part of the complex was based in ARM microcontroller. This measure made up to 0.5 millivolts per in the time interval from 10 nanoseconds.

The circuit includes two input channels for measuring voltage, ADC's and start signal detection part.Data is transmitted to a computer via USB.

With this method it is possible to measure the parameters of completely different samples, such as solid structures, optical films, nanostructures or heterostructures, and metamaterials.

In this paper demonstrated the results of measurements Si-Ge heterostructure with nanoislands. Used a neodymium laser with a wavelength of 1064 nm for second harmonic generation.

8857-8,

Conference overview

Oliver E. Drummond, CyberRnD, Inc. (United States)

This conference overview addresses the types of targets and the major characteristics of the data encountered in processing sensor data of these targets. The presentation summarizes why tracking these targets make the processing of this data so complex and challenging. The discussion includes a view of the algorithm state of the art, the current drivers in algorithm development, and the critical open issues. Future direction of this series of conferences is discussed and audience suggestions are invited.

8857-9, Session 2

Particle filter tracking for the banana problem

Kevin Romeo, Peter Willett, Yaakov Bar-Shalom, Univ. of Connecticut (United States)

In this paper we present an approach for tracking with a high-bandwidth active sensor in very long range scenarios. We show that in these scenarios the extended Kalman filter is not desirable as it suffers from major consistency problems, and that many types of particle filters may suffer from a loss of diversity among particles after resampling. This leads to sample impoverishment and the divergence of the filter. In the scenarios studied, this loss of diversity can be attributed to the very low process noise. However, a regularized particle filter is shown to avoid this diversity problem while producing consistent results. The regularization is accomplished using a modified version of the Epanechnikov kernel.

8857-10, Session 2

Particle flow with non-zero diffusion for nonlinear filters, Bayesian decisions and transport

Frederick E. Daum, Jim Huang, Raytheon Co. (United States)

We solve the transport problem in high dimensions by computing the flow of particles induced by Bayes' rule with a linear constant coefficient first order highly underdetermined PDE, similar to the Gauss divergence law. We pick a unique solution to this highly underdetermined PDE by using an upper triangular Jacobian of the flow, inspired by Knothe-Rosenblatt transport. One might call this "differential Knothe-Rosenblatt transport". We solve this PDE using the Fourier transform, but we avoid computing the inverse Fourier transform by use of Monte Carlo integration and the generalized matrix inverse (roughly analogous to a pseudodifferential operator). We show numerical results for high dimensional nonlinear filter problems (d = 1 to 30) with a wide variety of parameters (stable and unstable plants, initial uncertainty of the state vector, measurement accuracy, and dimension of the plant). This algorithm works for arbitrary smooth nowhere vanishing probability densities, including highly non-Gaussian multimodal densities, and hence the theory can be applied to essentially any estimation or Bayesian decision problem. We solve the fundamental and well known problem of particle degeneracy by using a log-homotopy of the conditional probability density, but we do not use resampling of particles or a proposal density, and we do not use Metropolis-Hastings or MALA or Hamiltonian Monte Carlo or any other Markov chain Monte Carlo method (MCMC), and our method is not anything like variational Bayes algorithms. It turns out that it is crucial to select an optimal set of points in k-space at which to evaluate the Fourier transform, and somewhat surprisingly we must enforce neutral charge density of particles to very high accuracy along the flow in order to guarantee the existence of a solution to our linear underdetermined PDE. Our algorithm is roughly ten orders of magnitude faster than standard particle filters for the same estimation accuracy.

8857-11, Session 2

A survey of maneuvering target tracking, part VId: sampling-based nonlinear filtering

Xiao-Rong Li, Vesselin P. Jilkov, Univ. of New Orleans (United States)

This paper is Part VId of a comprehensive survey of maneuvering target tracking without addressing the so-called measurement-origin uncertainty. It provides an in-depth coverage of various sampling-based nonlinear filters, commonly referred to as particle filters, developed particularly for handling the uncertainties induced by potential target maneuvers as well as nonlinearities in the dynamical systems commonly encountered in target tracking. Various implementations and tracking applications are reviewed. Some computational issues, such as different resampling schemes and parallel processing are addressed.

8857-12, Session 2

Estimability of thrusting trajectories in 3D from a single passive sensor with unknown launch location

Ting Yuan, Yaakov Bar-Shalom, Peter Willett, R. Ben-Dov, S. Pollak, Univ. of Connecticut (United States)

The problem of estimating the state of thrusting/ballistic endoatmospheric projectiles moving in 3-dimensional (3-D) space using 2-dimensional (2-D) measurements from a single passive sensor (stationary or moving with constant velocity) with unknown launch location is investigated. The unavailable knowledge of launch point (LP), which is a crucial practical issue for a correct and accurate impact point prediction (IPP), exacerbates the ambiguity problem that could exist in estimation. The estimability is analyzed based on the Fisher Information Matrix (FIM) of the target parameter vector, comprising the unknown LP height, initial launch (azimuth and elevation) angles, drag coefficient and thrust, which determine its trajectory according to a nonlinear motion equation. The full rank of the FIM ensures that one has an estimable parameter vector. The corresponding Cram{'{e}}r-Rao lower bound (CRLB) quantifies the estimation performance of the estimator that is statistically efficient and can be used for IPP. In view of the inherent nonlinearity of the problem, the maximum likelihood estimate (MLE) of the target parameter vector is found by using the iterated least squares (ILS) numerical approach. A drag-coefficient-thrust-height grid-based ILS search over the launch angles space is proposed. The grid-based ILS approach is shown to converge to the global maximum and its reliable estimation performance. This is then used for IPP.

8857-13, Session 2

A minimalist approach to bias estimation for passive sensor measurements with targets of opportunity

Djedjiga Belfadel, Richard. W. Osborne III, Yaakov Bar-Shalom, Univ. of Connecticut (United States)

In order to carry out data fusion, registration error correction is crucial in multisensor systems. This requires estimation of the sensor measurement biases. It is important to correct for these bias errors so that the multiple sensor measurements and/or tracks can be referenced as accurately as possible to a common tracking coordinate system. This paper provides a solution for bias estimation for the minimum number of passive sensors (two), when only targets of opportunity are available. The sensor measurements are assumed time-coincident (synchronous). Since these sensors provide only line of sight (LOS) measurements, the formation of a single composite Cartesian measurement obtained from fusing the LOS measurements from different sensors is needed to avoid the need for nonlinear filtering. The evaluation of the Cramer-Rao Lower Bound (CRLB) on the covariance of the bias estimate, i.e., the quantification of the available information about the biases, combined with simulations, shows that this method is statistically efficient, even for small sample sizes (as few as two sensors and six points on the trajectory of a single target of opportunity). We also show that RMS position error is significantly improved with bias estimation compared with the target position estimation using the original biased measurements.

8857-25, Session 2

On covariance structure in noisy, big data

Randy Paffenroth, Ryan Nong, Philip C. Du Toit, Numerica Corp. (United States)

Herein we describe theory and algorithms for detecting covariance structures in large, noisy data sets. Our work uses ideas from compressed sensing, matrix completion, and robust principal component analysis to detect the presence of low-rank covariance matrices, even when the data is noisy, distorted by large corruptions, and only partially observed. In fact, the ability to handle partial observations, combined with ideas from randomized algorithms for matrix decomposition, are the key enablers for producing asymptotically fast algorithms. While such methods have applicability to many problems, including mathematical finance, crime analysis, and other large-scale sensor fusion problems, our focus will be on applying these methods in the context of cyber network intrusion detection. In particular, our goal is to use such methods to detect anomalies in large-scale cyber data (e.g. pcap, NetFlow, etc.).

8857-22, Session P1

Estimating the quality of the software for inclusion recognizing and analyzing in semiconductor crystals

Liliya Dyachenko, Eugen Minov, Sergey E. Ostapov, Petro M. Fochuk, Oleg Kopach, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Aleksey E. Bolotnikov, Ralph B. James, Brookhaven National Lab. (United States)

In this paper, we discuss our software implementation for a series of infrared images that recognize and reveal the three-dimensional structures of defects in semiconductor crystals. Such programs often are used to explore the quality of various crystals, for example, CdTe and CdZnTe.

Despite the potential value of such crystal-recognition programs, one major problem here is whether researchers can confidently use them, because it is impossible to grow crystals with predetermined properties that can be used as a standard. There is another way to calibrate these programs to assure the trustworthiness of such recognition, viz., detecting a recognition threshold and acquiring a detailed knowledge of the influence of the parameters on the IR images. This task involves creating a program for generating "virtual crystals" with predetermined parameters of defects and comparing the "pictures" received from them with the properties of the virtual crystals.

Modeling the structure of defects in a semiconductor crystal is based on a series of infrared images that are stored in the *.jpg format. The software first undertakes the recognition of defects in the proposed images, and then builds a three-dimensional image of a subsystem of defects. The developed software provides tools for editing images, allowing defects originating from surface irregularities and defects of the image itself to be wiped out. The system offers the ability to display a specific group of defects, so allowing a view of only those specific extended defects that interest the user. The constructed three-dimensional image is rotatable via the computer's mouse.

8857-23, Session P2

Study on comparison and validation of the measured and simulated IR signal using the scaled model ship

Dong-Geon Kim, Kuk-Il Han, Jun-Hyuk Choi, Tae-Kuk Kim, Chung-Ang Univ. (Korea, Republic of)

The primary goal of the present study is to develop a S/W that predicts infrared signals from objects by synthetically considering the internal and external factors, such as surface properties, internal heat sources, solar irradiations, atmospheric temperature, etc. As a part of developing a S/W, this paper contains some results of the measured and simulated IR signals to comparing and validating. The scaled model ship used in this study is made of 5mm-thick steel and 1.5m long(scaled down by 1/100). It has virtual internal heat sources that are made of brass. At first, the surface temperature of the scaled model ship is measured in an indoor environment. The radiance from the ship is mainly based on the surface temperature because the effects of solar and wind are excluded in an indoors. Also the IR signals are collected by the IR cameras which are operated at MWIR(3~5µm and LWIR(8~9.2µm), respectively. At the same time, additionally, the atmospheric temperature and the relative humidity are measured to use for input conditions of calculation. The surface temperature and the IR signals within the two wavelengths are calculated by the S/W developed in this study with considering same conditions: the 3D ship model, the internal heat source temperature, the atmospheric temperature, and the relative humidity. The temperature and IR signals from the scaled model ship obtained from measurements and by using the S/W developed in this study are compared each other. The results show fairly good agreement with those obtained from measurements.

8857-24, Session P2

Research on pre-processing algorithm for transient electromagnetic signal

Huinan Zhao, Lingjia Gu, Ruizhi Ren, Jian Sun, Jilin Univ. (China)

Transient electromagnetic method (TEM) is regarded as an everlasting issue for geological exploration. The signal acquisition systems based on transient electromagnetic theory are widely used in many research fields, such as mineral exploration, hydrogeology survey and engineering exploration. The principle of transient electromagnetic method is to establish a first pulse magnetic field underground through the ungrounded loop with pulse current. During the period of the magnetic field downward diffusion, if the magnetic field encounters a good conductive geological body under the ground, it will produce eddy current in the geological body. A new magnetic field can be further induced in the geological body due to the eddy current changing with times, which is called the secondary magnetic field. Within the first pulse magnetic field intermittent, the receiver coil will couple with the secondary magnetic field. Through the late inversion process, the signal of underground conductor can be obtained. However, there are many serious random disturbance signals, namely, noises in the secondary field signal of the transient electromagnetic measurement system, which cause calculation errors in the late inversion. To solve this problem, an effective pre-processing algorithm for transient electromagnetic signal based on Labview virtual instrument development platform is proposed in the paper, which includes signal abnormality judgment, signal-to-noise ratio (SNR) judgment, signal superposition denoising, wavelet threshold denoising and wavelet packet denoising. The test results demonstrated that the proposed preprocessing algorithm can effectively eliminate serious disturbance signals from the test transient electromagnetic data, which can ensure efficiency of transient electromagnetic data in the late work.

8857-15, Session 3

Detection of unusual trajectories using multi-objective evolutionary algorithms and rough sets

Tomasz G. Smolinski, Trevor Newell, Samantha McDaniel, David D. Pokrajac, Delaware State Univ. (United States)

Detection of unusual trajectories of moving objects (e.g., people, automobiles, etc.) is an important problem in many civilian and military surveillance applications. The problem can be considered a two-class classification/prediction task: given a set of characteristic trajectories, can we build a classifier capable of recognizing typical, but yet unseen trajectories, and identify those that seem suspicious? Classificatory decomposition (CD) is a multi-objective evolutionary algorithms and rough sets-based signal decomposition technique that breaks down the original signals (e.g., 2-dimensional trajectories) into a set of additive components. However, instead of assuming orthogonality (as in Principal Component Analysis) or statistical independence (as in Independent Component Analysis) in the process of decomposition, the algorithm attempts to extract a small number of components (also called basis functions) that are most useful for the underlying classification problem. The main assumption in CD is that the basis functions are relatively constant for all of the observable signals (e.g., various aspects of movement across a scene), but are expressed differently due to some underlying classification scheme (e.g., typical vs. unusual trajectory). The variation of expression of the basis functions between different classes is characterized by the differences in the coefficients. A new trajectory is represented in the space spanned by the basis functions generated from the training set, and by matching it against a simple classifier, we can determine if said trajectory is typical, or if, perhaps, attention of a human operator is required. We test our approach on publicly available datasets, including the SENSIAC database.

8857-16, Session 3

Optical sensor pixel size selection from a tracking perspective

Richard W. Osborne III, Xin Zhang, Peter Willett, Yaakov Bar-Shalom, Univ. of Connecticut (United States)

This paper considers the selection of the resolution cell (pixel) size for the detection and tracking of point targets in the focal plane (FP) of an imaging sensor. For smaller pixels, the signal power in each resolution cell becomes lower, because a point target is recorded as a blur according to the point spread function (PSF). Meanwhile, since the noise power is proportional to the area of the resolution pixel, the noise is also lower. On the other hand, using a coarser resolution (which is the result of opting for a high signal power in the resolution cell) results in higher noise power. The various pixel sizes will also impact the measurement extraction scheme and result in varied levels of measurement noise, which will impact the target tracking accuracy. Therefore, as the pixel size changes, there is a trade-off in terms of detection performance versus estimation accuracy. The choice of pixel size is examined here from the perspective of maximizing the overall tracking accuracy. The pixel-size effects on the probability of detection and the measurement extraction accuracy (the FP position measurement noise variance) are analyzed. Expressions that allow calculation of these key quantities, necessary for the design of advanced tracking filters, are given. The impact of pixel size, target strength (SNR) and target motion uncertainty (its ``maneuvering index") on the tracking accuracy are quantified and illustrated with simulations.

8857-17, Session 3

Major challenges and rewards in improving fusion processing

Oliver E. Drummond, CyberRnD, Inc. (United States)

While small target signal and data processing has matured greatly, especially during the last twenty-five years, there still appears to be opportunities for substantial improvement in signal and data processing functional performance. This improvement in performance may require a substantial effort to deal with potentially very complex processing issues.

While this paper concentrates on fusion, the opportunities for improvement appears to extend to processing systems without fusion, however, the relative amount of improvement may be less. Three specific processing approaches for improvement in functional performance are addressed here. They are adaptive sensor data fusion; integration and interaction of the processing of sensor data fusion functions; and advanced fuse-before-detect. To help simplify the discussion, a distinction is made between sensor data fusion and multiple sensor tracking. The difference is that sensor data fusion includes functions that take advantage of multiple sensor tracks to improve target typing/classification plus resource management, such as communications, processing, and weapon resources.

8857-18, Session 3

Target track extraction in high false density environments using multiple hypothetical frame selection MLPDA

Masanori Mori, Takashi Matsuzaki, Hiroshi Kameda, Toru Umezawa, Mitsubishi Electric Corp. (Japan)

MLPDA (Maximum Likelihood Probabilistic Data Association) has been attracted as an effective target track extraction algorithm in high false density environments. In this algorithm, the target track is estimated as the maximum likelihood state vector, by using multiple observation frames which include the target signal and many false signals. The track is confirmed whether it is the true target or not, by comparing its likelihood with a given track confirmation threshold. However, when the target signals are lost at several frames, the conventional MLPDA deteriorates the track estimation accuracy due to false signals in frames without the target signal.

In this paper, we propose multiple hypothetical frame selection MLPDA, which can extract the target track under the situation where the target signals are lost in several frames. In particular, a batch of stored frames is first selected for track extraction. If the track is not confirmed, our algorithm offers multiple frame selection hypotheses where some frames are assumed as the frames without the target signal and the other frames include the target signal. The track is extracted under these hypotheses respectively, and the most-likely hypothesis is accepted. If all hypotheses are rejected, our proposed method generates hypotheses that increase the number of frames without the target signal, and verifies them again. Furthermore, the hypotheses which have likelihoods above a given threshold are retained in order to modify the wrong frame selection later. Simulation results show the validity of our proposed method.

8857-19, Session 3

Directional sensor control for maximizing information gain

Shankarachary Ragi, Colorado State Univ. (United States); Hans D. Mittelmann, Arizona State Univ. (United States); Edwin K. P. Chong, Colorado State Univ. (United States)

Directional sensors (e.g., surveillance cameras, infrared sensors, and ultrasound sensors) are gaining importance due to applications including surveillance, detection, and tracking. We develop tractable solutions to the problem of controlling multiple 2-D directional sensors for maximizing information gain corresponding to multiple targets located on a 2-D plane. The location of the targets is known with uncertainty given by a joint a-priori distribution (Gaussian), and the sensor locations are known exactly. A directional sensor has a limited field-of-view (FOV), where the area sensed by the sensor is given by a sector in a circular region around the sensor. The direction of a sensor can be controlled, which can take several discrete values. A directional sensor generates a measurement of a target if and only if the target lies within the FOV of the sensor. We have a notional fusion center where the measurements from all the sensors are fused. Our goal is to assign each sensor to a particular angle such that the overall information gain is maximized. This problem is hard to solve exactly because of its combinatorial nature—the computation time increases exponentially with the number of sensors. We develop heuristic approaches that are tractable and give sub-optimal solutions, and also provide lower bounds on the optimal information gain. We also solve a relaxed version of the problem that yields an upper bound on the optimal information gain. We conduct an empirical study to compare the performance of these approaches.

8857-20, Session 3

Efficient multiple emitter localization for fully decentralized large-scale/low-cost multimodal sensor networks

Philip J. Haney, BAE Systems (United States); Paul D. Fiore, MIT Lincoln Lab. (United States)

Recent advances in wireless communications and sensing technologies have led to ongoing interest in developing large-scale sensor networks for detecting, localizing and tracking emitters of interest for wide-area persistent surveillance applications. In order for such large-scale networks to be feasible, low-cost becomes paramount and is typically achieved through the incoherent combination of inexpensive sensors dispersed throughout the surveillance region of interest. Since low-cost sensors stereotypically exhibit multimodal characteristics, achieving accurate emitter localization and tracking performance throughout the network presents a challenging problem. Typical multimodal localization methodologies using simple intersection approaches frequently produce

sub-optimal performance generating numerous false tracks ultimately leading to significant degradation in tracking performance. Alternatively, more robust methods for performing multimodal localization have been proposed; however, these methods rooted in computationally expensive operations such as Sequential Monte Carlo Methods and multiple hypothesis tracking are not suited for large-scale, low-cost sensor network applications. As a result, this paper adopts both a robust and computationally efficient approach to the multimodal localization problem by generating a pseudo maximum likelihood (PML) function from available sensor measurements in which the peaks of this function strongly indicate the number and locations of the true emitters. Localization is performed by first iteratively associating the individual sensor measurements to the PML peaks and then generating true maximum likelihood estimates of the emitter locations based on the associated measurements. These emitter location estimates are fed to an EKF-based, decentralized architecture for initiating, sustaining and sharing local track activity throughout the sensor network. Simulation results illustrate the ability of the proposed localization approach to generate accurate emitter location estimates in cluttered environments for supporting all track activity in large-scale, fully decentralized, multimodal sensor networks.

8857-21, Session 3

Multitarget tracking using ABIR images and the H-PMHT

Balakumar Balasingam, Peter Willett, Univ. of Connecticut (United States); Darin T. Dunham, Terry Ogle, Vectraxx, Inc. (United States)

In this paper, we address the problem of passive tracking of multiple targets with the help of images obtained from airborne infrared (ABIR) platforms. Conventional approach to this problem, which involves thresholding, measurement detection, data association and filtering, encounters problems in every steps due to the fact that the target energy is spread in multiple cells of the ABIR imagery. A histogram based probabilistic multi-hypothesis tracking (H-PMHT) approach provides an automatic means of modeling targets that are spread in multiple cells in the imaging sensor(s) by relaxing the need for hard decisions on measurement detection and data association. With the help of simulated ABIR images from multiple platforms, we demonstrate the applicability of H-PMHT for tracking 3D targets.

8858-1, Session 1

Image inpainting: theoretical analysis and comparison of algorithms

Emily J. King, Gitta Kutyniok, Technische Univ. Berlin (Germany); Xiaosheng Zhuang, City Univ. of Hong Kong (China)

An issue in data analysis is that of incomplete data, for example a photograph with scratches or seismic data collected with fewer than necessary sensors. There exists a unified approach to solving this problem and that of data separation: namely, minimizing the norm of the analysis (rather than synthesis) coefficients with respect to particular frame(s).There have been a number of successful applications of this method recently. Analyzing this method using the concept of clustered sparsity leads to theoretical bounds and results, which will be presented. Furthermore, necessary conditions for the frames to lead to sufficiently good solutions will be shown, and this theoretical framework will be use to show that shearlets are able to inpaint larger gaps than wavelets. Finally, the results of numerical experiments comparing this approach to inpainting to numerous others will be presented.

8858-2, Session 1

Sparse representations for the morphological reconstruction of neurons from fluorescent microscopy images

Manos Papadakis, David Jimenez, Paul Hernandez-Herrera, Burcin Ozcan, Demetrio Labate, Univ. of Houston (United States); Fernanda Laezza, The Univ. of Texas Medical Branch (United States); Ioannis A. Kakadiaris, Univ. of Houston (United States)

We present a number of algorithms for segmenting the image of a live neuron from its background and for extracting dendritic/axonal centerlines and for identifying other important anatomical and functional elements of the post and pre-synaptic network. The input images are acquired with confocal or multiphoton microscopes. We demonstrate how a sparse representation can be designed by mixing isotropic filters which work as singularity detectors with directionally selective shearlet filters. We also report on our ongoing and recent experiments.

8858-3, Session 1

Parabolic molecules: curvelets, shearlets, and beyond

Gitta Kutyniok, Technische Univ. Berlin (Germany); Philipp Grohs, ETH Zürich (Switzerland)

Anisotropic representation systems such as shearlets and curvelets have had a significant impact on applied mathematics in the last decade. The main reason for their success is their superior ability to optimally resolve anisotropic structures. By now, a large variety of such anisotropic systems has been introduced such as curvelets and shearlets. In this talk we will introduce the concept of parabolic molecules which allows for a unified framework encompassing all known anisotropic frame constructions based on parabolic scaling. The main result essentially states that all such systems share similar sparse approximation properties.

8858-4, Session 1

A multiscale representation for efficient inference on permutations

Yue M. Lu, Harvard Univ. (United States)

Uncertainties over permutations are encountered in many problems, such as tracking, voting, and ranking. The factorial size of the permutation group makes efficient statistical inference a challenging problem. Fourier-theoretical ideas have been explored, since at least the 1980s, as a useful tool for tractable and approximate inference over permutations. We present our preliminary results on constructing an adaptive multiscale representation on the permutation group, achieving better trade-offs between accuracy and complexity than Fourier transforms.

8858-5, Session 1

A split-augmented Lagrangian algorithm for spectral factorization of a set of 2D directional filters and application to the design of compact shearlet frames

Bart Goossens, Jan Aelterman, Hiep Q. Luong, Aleksandra Pižurica, Wilfried Philips, Univ. Gent (Belgium)

In this paper, we first briefly review the directional properties of the Dual-Tree complex wavelet transform and we explain how the the directional selectivity of the transform can be increased (i.e., to obtain more than 6 orientations per scale). Inspired by this approach, we describe a new augmented Lagrangian optimization algorithm to jointly perform the 2D spectral factorization of a set of 2D directional filters, with high numerical accuracy. We demonstrate how this approach can be used to design compactly supported shearlet frames that are almost tight. Finally, a number of experimental results are given to show the merits of the resulting shearlet frames.

8858-6, Session 1

Optimal restoration of noisy 3D x-ray data via Shearlet decompositions

Demetrio Labate, Univ. of Houston (United States); Glenn R. Easley, System Planning Corp. (United States); Kanghui Guo, Missouri State Univ. (United States)

In a recent work, it was shown that the shearlet representation provides a useful formula for the reconstruction of 3D objects from their X-ray projections. One major advantage of this approach is that it yields a near-optimal rate of convergence in estimating piecewise smooth objects from 3D X-ray projections which are corrupted by white Gaussian noise. In this work, we provide extensive numerical demonstrations to illustrate the effectiveness of this method and its performance as compared with other state-of-the-art X-ray data restoration algorithms.

8858-7, Session 2

Interplay in various settings between translation invariant spaces, sampling, and wavelets *(Keynote Presentation)*

Guido L Weiss, Edward N Wilson, Peter M Luthy, Washington Univ. in St. Louis (United States)

We will begin with the description of principal translation invariant spaces

in L^2 (R) and their representation by weighted spaces L^2([-1/2,1/2), p). We extend these results to higher dimensions and describe their role in sampling and wavelet theory. We then generalize these results to higher dimensions and to the setting of more general spaces acted upon by locally compact abelian groups and their duals. We finish by further extending these results to certain non-abelian groups including the Heisenberg group.

8858-8, Session 3

Eigenvector localization, random matrices, and Banach algebras

Thomas Strohmer, Univ. of California, Davis (United States)

The phenomen of eigenvector localization has confounded mathematicians and physicists for more than half a century. Its most famous manifestation is known under the name of Anderson localization. I will report on recent progress on eigenvector localization at the interface of random matrices and Banach algebras. We are now able to give precise predictions about the qualitative and quantitative localization behavior of eigenvectors based on the localization characteristics of the matrix and certain properties of the spectrum.

8858-9, Session 3

Which sensing matrices allow for stable compressed sensing?

Dustin G. Mixon, Air Force Institute of Technology (United States); Jameson Cahill, Peter G. Casazza, Univ. of Missouri-Columbia (United States)

In compressed sensing, it is popular to reconstruct sparse signals using L1 minimization. In this setting, the null space property (NSP) is necessary and sufficient for unique recovery, whereas the restricted isometry property (RIP) is sufficient for stability. In this talk, we consider a different notion of stability, and we identify a new matrix property which guarantees this stability. In particular, we identify that a well-conditioned sensing matrix can be beneficial, despite not being required by RIP. This leads to new constructions of "good" sensing matrices, while at the same time motivating the construction of tight frames for compressed sensing.

8858-10, Session 3

Spectral methods for extracting localized features from dual data

Nate K. Strawn, Duke Univ. (United States)

Deep learning has been making fast gains since the work of Hinton, Osindero, and Teh (2006). Their fast stochastic gradient descent method for training layers of restricted Boltzmann machines produced the best results (for their time) on classification of image data sets. Inspired by the fact that the first layers of Hinton et al.'s tend to learn features similar to directional filters, Lee, Grosse, Raganath, and Ng (2009)combined the RBM model with Lecun's convolutional neural networks to further break classification records on image data sets. These deep learning results represent incremental steps towards fully utilizing the natural pixel (or dual data) topology of images. For more exotic data sets, the underlying geometry of the dual data is not readily available. In our work, we demonstrate from theory and practice that spectral methods provide a bountiful framework for discovering generic dual data topologies and extracting localized (sparsely supported) features.

8858-11, Session 3

Sub-Gaussian random frames, Sobolev duals, and root-exponential accuracy for sigma-delta quantization

Ozgur Yilmaz, The Univ. of British Columbia (Canada); Felix Krahmer, Univ. Sternwart Göttingen (Germany); Rayan Saab, Duke Univ. (United States)

There is a rich literature on frame quantization, though the main focus has been on structured frames. Motivated by compressed sensing we focus on unstructured sub-Gaussian random frames. We show that by using sigma-delta quantizers along with reconstruction via "Sobolev duals", we can effectively quantize sub-Gaussian frame expansions. Specifically, we prove that using an r-th order sigma-delta scheme, we get an accuracy of order (-r)-th power of the "aspect ratio" of the frame. Furthermore, if we optimize the order of the scheme depending on the aspect ratio, this yields root-exponential accuracy.

8858-12, Session 3

Exact signal recovery from thresholded measurements

Friedrich Philipp, Holger Boche, Gitta Kutyniok, Mijail Guillemard, Technische Univ. Berlin (Germany)

We study the exact recovery of signals from linear measurements which are erased when their magnitude is smaller than a given threshold parameter.

8858-13, Session 4

Dynamical sampling: exact reconstruction from sensing networks

Akram Aldroubi, Vanderbilt Univ. (United States)

Let $Vsubset L^2$ be a shift invariant subspace and $fin V$ be an initial distribution that is evolving in time under the action of a family of (spatially) invariant evolution operators ${A_t}_{tin [0,infty)}$:

begeqlabel{evo1}

f_t(x) = (A_t f)(x).

end{equation}

Let X_m be the set $mmathbb Z$, $minNN$. We study the conditions under which $f=f_0$ can be recovered from the samples ${ f(X_m),(A_1 f)(X_m),dots, (A_T f)(X_m)}cup {f(Omega)}$ in a stable way, where $Omegasubset ZZ$ is a small extra sampling sets judiciously chosen.

This work is in Collaboration with Jacque Davis and Ilya Krishtal

8858-14, Session 4

Random fusion frames for loss-insensitive packet encoding

Bernhard G. Bodmann, Univ. of Houston (United States)

This talk describes recent results on fusion frame design which are motivated by communication theory. Fusion frames are a natural tool for the linear encoding of an analog signal in packets that are transmitted through a network. The possible linear dependencies among vectors from the subspaces of a fusion frame incorporate redundancy in the encoded components of an analog signal, which allows to test the integrity of the transmitted data and to correct errors, for example the loss of part of the packets during the transmission. Essential techniques for fusion frame design in this context come from the literature on compressed sensing.

8858-15, Session 4

Preconditioning of frames

Gitta Kutyniok, Technische Univ. Berlin (Germany); Friedrich Philipp, Technische Univ. Clausthal (Germany); Kasso A. Okoudjou, Univ. of Maryland, College Park (United States)

Frames which are tight might be considered optimally conditioned concerning their numerical stability. This leads to the question of perfect preconditioning of frames, i.e., modification of a given frame to generate a tight frame. In this talk, we analyze prefect preconditioning of frames by a diagonal operator. We derive various characterizations of functional analytic and geometric type of the class of frames which allow such a perfect preconditioning.

8858-16, Session 4

Theoretical bounds on reconstruction from magnitudes of frame coefficients

Radu V Balan, Univ. of Maryland, College Park (United States)

We will present recent results about injectivity of the nonlonear map alpha:C^n -> R^m , (alpha(x))_k = |< x,f_k>|.

8858-17, Session 5

Sampling theory, wavelets, and sparse reconstruction on the sphere

Jason D. McEwen, Univ. College London (United Kingdom); Yves Wiaux, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We review recent developments in signal processing on the sphere, focusing on three related areas. Firstly, we discuss a novel sampling theorem on the sphere which halves the Nyquist rate on the sphere for equiangular sampling schemes. Secondly, we describe exact wavelet transforms on the sphere built from a tiling of harmonic space. Our novel sampling theorem leads to faster and more efficient algorithms to perform wavelet transforms on the sphere. Thirdly, we consider the application of the aforementioned methods for sparse reconstruction on the sphere.

8858-18, Session 5

Flaglets on the ball for studying the large-scale structure of the Universe

Boris Leistedt, Jason D. McEwen, Univ. College London (United Kingdom)

We define the Fourier-Laguerre transform -- a novel transform on the three-dimensional ball -- by combing the spherical harmonics on the sphere with damped Laguerre polynomials on the radial line. Unlike the Fourier-Bessel expansion, the Fourier-Laguerre transform admits a sampling theorem. We construct exact wavelets on the ball through a tilling of the Fourier-Laguerre harmonic space. The resulting ‘flaglets’ may be used to extract scale-dependent, spatially localised features from data defined on the ball. We use flaglets to study the statistical properties of clusters and voids in galaxy surveys and to constrain models of the large-scale structure of the universe.

8858-19, Session 5

3D sparse representations on the sphere and applications in astronomy

Jean-Luc Starck, Commissariat à l’Énergie Atomique (France); Francois Lanusse, Commissariat à l’Energie Atomique (France)

We present several 3D sparse decompositions based on wavelets and curvelets on the sphere that are useful for different kind of data set such as regular 3D spherical measurements (r, theta, phi), multichannel spherical measurements (lambda, theta, phi) or polarized data (stokes parameter, theta, phi). We show how these new decompositions can be used for astronomical data denoising and deconvolution, when the data are contaminated by Gaussian and Poisson noise.

8858-20, Session 5

Spatio-spectral formulation and design of spatially varying filters for signal estimation on 2-Sphere

Zubair Khalid, Rodney A. Kennedy, Parastoo Sadeghi, Salman Durrani, The Australian National Univ. (Australia)

In this paper, we consider the problem of estimation of a non-stationary signal in the spatio-spectral domain, when the signal is subject to distortion and noise. The estimation of such signal in spatial or spectral domain is not adequate. By using the framework presented in the literature for signal transformation in the spatio-spectral domain, we develop optimal filter (signal estimator) in the spatio-spectral domain that deals with the non-stationarity of the signal. The spatio-spectral filtering is based on the spatially localized spherical harmonic transform (SLSHT) representation of a signal in the spatio-spectral domain. We then extend our spatio-spectral filter to develop weighted multiple window spatio-spectral filter, where different window functions are used for obtaining SLSHT representation of a signal. It is shown that the use of orthogonal windows obtained as eigenfunctions of the Slepian concentration problem on the sphere achieves good performance.

8858-21, Session 5

Classification and construction of closed-form kernels for signal representation on the 2-sphere

Rodney A. Kennedy, Parastoo Sadeghi, Zubair Khalid, The Australian National Univ. (Australia); Jason D. McEwen, Univ. College London (United Kingdom)

This paper considers the construction of reproducing kernel Hilbert Spaces~(RKHS) on the sphere as an alternative to the conventional Hilbert space using the inner product that yields the $L^2(S^2)$ function space of finite energy signals. In comparison with wavelet representations which have multi-resolution properties on $L^2(S^2)$, the representations that arise from the RKHS approach which uses different inner products have an overall smoothness constraint which may offer advantages and simplifications in certain contexts. The key contribution of this paper is to construct a classes of closed-form kernels, such as one based on the von-Mises Fisher distribution, which permits efficient inner product computation using kernel evaluations. Three cases of RKHS classes are defined: isotropic kernels and non-isotropic kernels both with spherical harmonic eigenfunctions, and general anisotropic kernels.

8858-22, Session 5

A spatiospectral localization approach for analyzing and representing vector-valued functions on spherical surfaces

Frederik J. Simons, Alain Plattner, Kevin W. Lewis, Princeton Univ. (United States)

In satellite geomagnetic research today, the data are vector-valued, collected at an altitude above the source, and their analysis and interpretation in terms of source models requires an often ill-conditioned inversion. Especially when the data are noisy and the area over which data are available, or over which information is being sought, is less than an entire sphere, proceeding by localization is a very fruitful approach. Scalar Slepian functions have been very successful at extracting spatiospectrally localized information from noisy data acquired by satellites, but until recently no framework existed for the treatment of vector fields. We have constructed vector-valued spherical basis functions, quadratically concentrated over arbitrary spatial domains, and illustrate their use for applications in satellite geomagnetism.

We are combining some recent, and some new results on vectorial localization on the sphere, with a special emphasis on harmonic fields for use in geomagnetism and related areas, e.g. medical imaging.

8858-23, Session 6

Combining multiple observations of audio signals

Ilker Bayram, Istanbul Technical Univ. (Turkey)

We consider the problem of reconstructing an audio signal from multiple observations, each of which is contaminated with time-varying noise. Assuming that the time-variation is different for each observation, we propose an estimation formulation that can adapt to these changes. Specifically, we postulate a parametric reconstruction and choose the parameters so that the reconstruction minimizes a cost function. Since the reconstruction is expected to be an audio signal, the cost function is selected so that audio signals are penalized less, compared to arbitrary signals with the same energy. As cost functions, we experiment with a recently proposed prior as well as mixed norms placed on the short time Fourier coefficients. Both of these cost functions allow to make use of the structured sparsity inherent in audio signals, in order to separate them from arbitrary signals. Thanks also to the special forms of these functions, we can express the estimation formulation as a saddle point problem. In order to solve the resulting saddle point problem, we employ recent algorithms proposed for such problems. As a further enhancement, we add regularization terms that apply directly on the parameters to be optimized. This direct regularization helps to incorporate known information about the noise terms, like smooth variation of their characteristics over time, leading to an improved reconstruction.

8858-24, Session 6

Hybrid approximate message passing methods for structured compressed sensing

Sundeep Rangan, Polytechnic Institute of New York Univ. (United States); Alyson K. Fletcher, Univ. of California, Santa Cruz (United States)

Approximate message passing (AMP) refers to a recently-developed class of graphical models-based algorithms for estimation of random, possibly non-Gaussian, vectors x from high-dimensional linear measurements. AMP methods have attracted considerable recent attention in the context of compressed sensing due to their computational simplicity, generality and analytic tractability. However, a key limitation of the AMP methodology is the requirement that the components of the vector x are independent, limiting the ability to incorporate other structural information in the prior on x that is critical in many practical compressed sensing problems. This paper presents a novel method called Hybrid Generalized AMP (HyGAMP) that extends the AMP methods to vectors x with priors described by general graphical models. The formulation can incorporate a wide class of structured sparse representations, including group sparsity and correlated sparsity modeled via general Markov random fields. Certain latent variables and hyper-parameters can also be incorporated into the model. The HyGAMP algorithm operates by representing the overall system as a larger graphical model partitioned into components with linear, dense dependencies along with stronger, possibly nonlinear, sparse relationships. Estimation is then performed by combining standard loopy belief propagation updates along the sparse, nonlinear, components of the graph with AMP-type updates in the dense, linear section.The formulation is extremely general and we demonstrate the effectiveness of the HyGAMP methodology in sparse multinomial regression problems as well as image denoising with multiple transforms.

8858-25, Session 6

On linear transform design with non-linear approximation

Osman G. Sezer, Texas Instruments Inc. (United States); Onur G. Guleryuz, FutureWei Technologies, Inc. (United States)

In this paper we share our recent observations on methods for sparsity enforced orthogonal transform design. In our previous work on this issue, our target was to design transforms that will minimize overall sparsity-distortion cost of a collection of image patches mainly for improving the performance of compression methods. In this paper we go one step further to understand why these transforms achieve better approximation and how different they are from transforms like the DCT or the Karhunen-Loeve transform (KLT). Our study lead us to mathematically validate that for a Gaussian process the KLT is the optimal transform not only in a lienar approximation sense but also in a nonlinear approximation sense, the latter forming the basis for sparsity-based regularization.

This means our transform design method yields the KLT in Gaussian processes, yet distinctly differentiates itself from the KLT in non-Gaussian cases by capturing useful structures within the data. Both toy examples and real compression results in various representation domains are presented in this paper to support our observations.

8858-26, Session 6

Group sparse optimization by alternating direction method

Wei Deng, Wotao Yin, Yin Zhang, Rice Univ. (United States)

Group sparsity is an emerging terminology that characterizes the underlying sparsity and structure of the data. Real-world data (such as audio signals, images and videos) is often highly sparse and richly structured. Group sparsity techniques, by taking advantage of the sparsity and structural information in the data, will facilitate more efficient ways to tackle large and complicated data in practice. We develop efficient algorithms for solving a class of optimization problems with group sparse solutions, which arise in various applications such as compressive sensing, statistics, signal and image processing, machine learning and computer vision. The mixed $L_{2,1}$-norm is used to promote group sparsity. But the resulting problems can be quite challenging to solve due to the nonsmoothness, mixed-norm structure and possible grouping irregularities. Our approach is based on a variable splitting strategy and the alternating direction methodology. The proposed algorithms are first-order methods, suitable for large-scale computation. The per-iteration computational cost is reasonably low, which is roughly two matrix-vector multiplications. Extensions of the algorithms can be easily made to enforce nonnegativity in the data and allow arbitrary grouping structures such as overlapping groups. The global convergence of our algorithms is guaranteed by the existing theory of the alternating direction method. We also extend the convergence theory to allow more generality and more options of solving the subproblems. Extensive numerical results are presented to demonstrate the efficiency, stability and robustness of the proposed algorithms, in comparison with the previously known state-of-the-art algorithms.

8858-27, Session 7

Randomized sampling in exploration seismology *(Keynote Presentation)*

Felix J. Herrmann, The Univ. of British Columbia (Canada)

No Abstract Available

8858-28, Session 8

A unified framework for 3rd generation lidar pulse processing based on finite rate of innovations

Charles D. Creusere, Juan Castorena, New Mexico State Univ. (United States)

In this paper, we will introduce a LIDAR return pulse analysis framework based on the concept of finite rate of innovations (FRI). Specifically, the proposed FRI-based model allows us to characterize the temporal return pulse envelopes captured by 3rd generation LIDAR systems in a low dimensional space. Furthermore, the extracted model parameters can be shown in many realistic scenarios to map to specific physical features of the scene being captured. After describing the model formulation and extraction process, we will illustrate its potential utility in two specific applications: sub-spot size ranging (super-resolution) and random impulsive scene sampling. Because of space limitations in this extended abstract, we will discuss only the pulse modeling aspect of our work here. In the actual paper, however, we will also present results illustrating the utility of our model for both random impulsive scene sampling and super-resolution.

8858-29, Session 8

MAP recovery of B-spline from compressive samples and its application to vehicular signals

Akira Hirabayashi, Yamaguchi Univ. (Japan); Satoshi Makido, Toyota Central R&D Lab. (Japan); Laurent Condat, Grenoble Institute of Technology (France)

We propose a stable reconstruction method for B-spline signals from compressive samples based on maximum a posteriori (MAP) estimation. The B-spline is one of the most powerful tools for modeling signals in real applications. Since such functions are not band-limited, the classical sampling theorem cannot be applied to them. However, splines can be regarded as signals with finite rate of innovation and therefore be perfectly reconstructed from noiseless samples acquired at, approximately, the rate of innovation. Our approach based on MAP estimation reconstructs the signals stably from noisy samples, more efficiently than the conventional methods that use the so-called annihilating filter. We show the effectiveness of our method by applying it to compressive sampling of vehicular signals.

8858-30, Session 8

Sampling great circles at their rate of innovation

Samuel Deslauriers-Gauthier, Pina Marziliano, Nanyang Technological Univ. (Singapore)

In our previous work, we extended signals that can be sampled and reconstructed at their rate of innovation to include Diracs defined on the sphere in 3D Euclidean space. Here, we show that great circles, the intersection of a plane through the origin and a sphere centered at the origin, can be reconstructed using similar methods. Specifically, we show that 2K(4K - 1) samples are sufficient to exactly recover K great circles. The sampling scheme involves a kernel defined on the 3D rotation group which allows us to recover a subset of the spherical harmonic coefficients of the great circles. We then show that the parameters of the great circles can be extracted from these coefficients. The performance of our method is illustrated using several numerical simulations.

8858-31, Session 8

3D imaging of simple scenes using parametric signal processing

Andrea Colaco, Ahmed Kirmani, Jonathan Mei, Nan-Wei Gong, Vivek K. Goyal, Massachusetts Institute of Technology (United States)

We introduce a new architecture for optical sensing of 3D structure of simple scenes that is based on parametric modeling and processing of scene impulse responses. In contrast to conventional techniques, this framework offers simplicity of hardware, high frame rates, compact form factors, insensitivity to ambient light, and low power. Our method is not intended for high spatial resolution 3D imaging of general scenes, but rather high accuracy localization and tracking of specific scene features. Simulations and initial hardware experiments demonstrate two potential applications: localization of two hands for a gestural interface and estimation of plane position and pose for augmented reality.

8858-32, Session 8

A sampling theorem for sparse signals on the sphere

Yue M. Lu, Harvard Univ. (United States)

Signals defined on the two dimensional sphere are encountered in many domains, including geophysics, astronomy, quantum chemistry, and spatial audio acquisition. We develop a novel sampling theorem for reconstructing K-sparse signals on the sphere from O(K^2) samples. The proposed reconstruction algorithm is computationally efficient. It is also shown to be robust in the presence of noise. Two applications are presented: 1. localizing diffusion sources using a small number of irregularly placed sensors; and 2. removing shot noise in the samples of bandlimited functions on the sphere.

8858-33, Session 8

Approximate Strang-Fix: sampling infinite streams of Diracs with any kernel

Pier Luigi Dragotti, Jon Onativia, Antonio Uriguen, Imperial College London (United Kingdom); Thierry Blu, The Chinese Univ. of Hong Kong (China)

In the last few years, several new methods have been developed for the sampling and the exact reconstruction of specific classes of non-

bandlimited signals known as signals with finite rate of innovation (FRI). This is achieved by using adequate sampling kernels and reconstruction schemes. An important class of kernels is the one made of functions able to reproduce exponentials.

In this paper we depart from the situation in which we can choose the sampling kernel and develop a new strategy that is universal in that it works with any kernel. We do so by noting that meeting the exact exponential reproduction condition is too stringent a constraint, we thus allow for a controlled error in the reproduction formula in order to use the exponential reproduction idea with any kernel and develop a reconstruction method which is more robust to noise.

Moreover we propose a novel method that is able to reconstruct infinite streams of Diracs, even in high noise scenarios. We sequentially process the discrete samples and output locations and amplitudes of the Diracs in real-time. We first establish conditions for perfect reconstruction in the noiseless case and then present the sequential algorithm for the noisy scenario. We also show that we can achieve a high reconstruction accuracy of 1000 Diracs for SNRs as low as 5dB.

8858-35, Session 9

Joint image registration and reconstruction from compressed multi-view measurements

Gilles Puy, Pierre Vandergheynst, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We present a method for joint reconstruction of a set of images, representing a same scene, from few linear multi-view measurements. We model the correlation between the measurements using geometric transformations represented by few parameters. The proposed method estimates both these parameters and the observed images using the measurements as the sole information. It is also robust to occlusions. The reconstruction algorithm minimizes a non-convex functional and generates a sequence of estimates converging to a critical point of this functional. We show the efficiency of the algorithm in compressed sensing applications.

8858-36, Session 9

Real-time compressive video using coded aperture cameras

Thomas A. Goldstein, Richard G. Baraniuk, Rice Univ. (United States)

Single-pixel cameras" are a new modality for image acquisition using compressive measurements. In contrast to conventional imaging, which relies on arrays of many photodetectors, single picture cameras obtain high resolution images using only a single detector. This is accomplished using a "coded aperture," which compresses global image information into each measurement rather than observing one pixel at a time. In this talk, we discuss the challenges of applying these new compressive imaging tools to video acquisition. Compressive video poses many challenges that imaging does not. We are no longer imaging a static scene, but rather we must explicitly model the motion of objects and exploit correlations between adjacent frames. Furthermore, real-time reconstruction of video from compressive measurements requires the use of sophisticated numerical algorithms and parallel hardware implementations.

8858-37, Session 9

Sparsity and cosmology: inverse problems in cosmic microwave background experiments

Florent Sureau, Jérome Bobin, Jean-Luc Starck, Commissariat à l'Énergie Atomique (France)

Full-sky Cosmic Microwave Background (CMB) missions such as Planck or WMAP aims at providing key information about the structure and evolution of our universe as well as breakthroughs in the knowledge of the interstellar medium and extra-galactic emissions.These objectives are challenged by the mixing in between the CMB and these various components in the observed multichannel data. In this presentation, we will illustrate how the sparsity of the components can be used in various inverse problems in component separation and restoration, and how these problems can be solved based on recent works in optimization theory.

8858-39, Session 9

Optimal wavelet decomposition of sparse stochastic processes

Michael Unser, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Sparse stochastic processes are continuous-domain processes that admit a parsimonious representation in some matched wavelet-like basis. Such models are relevant for image compression, compressed sensing, and, more generally, for the derivation of statistical algorithms for solving ill-posed inverse problems.

In this presentation we shall provide theoretical evidence that Haar wavelets are optimal for the representation of certain non-Gaussian brands of Lévy processes and that they outperform the Karhunen-Loève transform.

8858-40, Session 10

Coding and sampling for compressive x-ray tomography

David J. Brady, Duke Univ. (United States)

Coded apertures and energy resolving detectors may be used to improve the sampling efficiency of x-ray tomography and increase the physical diversity of x-ray phenomena measured. Coding and decompressive inference enable increased molecular specificity, reduced exposure and reduced scan times.

8858-41, Session 10

Compressive sensing with quadratic phase systems and examples in optics

Adrian Stern, Yair Rivenson, Ben-Gurion Univ. of the Negev (Israel)

Spatial and temporal quadratic phase filters represent the behavior of many processes in various fields (e.g. optical, radar, sonar etc.) and applications. Here we examine the applicability of QPS as compressive sensing operators. Compressive sensing is a joint signal acquisition-reconstruction paradigm, which has gained much attention recently since it provides a framework for the reconstruction of highly subsampled signals. Convolution with quadratic phase kernels represents many spatial and temporal systems. This, together with the fact that under certain conditions quadratic phase filters (QPF) share similar features to Fourier transform operator, makes them an attractive choice for compressive sensing implementation. It is shown that CS performance of quadratic phase systems depends on the specific implementation parameters such as sampling intervals and quadratic phase filter parameter. For example, in the case that the QPF represents optical field propagation, it is shown that in the near field regime the number of measurements needed to fully reconstruct an object is proportional to the object's Fresnel number, while in the far field the number of measurements is in the order of the signal's sparsity level times a log factor.

The fact that QPF exhibit efficient CS behavior has been utilized for systems involving sparse aperture and sparse detector arrays, imaging behind partially opaque media and 3D object reconstructed from propagated fields. It has also been proved useful for tomography of three dimensional objects from a single two dimensional projection. This problem is highly ill-posed. We discuss the conditions for the solution of such problem and show its relation with the physical quantities of the object and of the detector.

8858-42, Session 10

Lens-free computational microscopy

Aydogan Ozcan, Univ. of California, Los Angeles (United States)

Today there are around 6 billion cell-phone users in the world, and the majority of these cellphones are being used in the developing parts of the world. This massive volume of wireless phone communication brings an enormous cost-reduction to cellphones despite their sophisticated hardware and software capabilities. Utilizing this advanced state of the art of the cell phone technology towards point-of-care diagnostics and/or microscopic imaging applications can offer numerous opportunities to improve health care especially in the developing world where medical facilities and infrastructure are extremely limited or even do not exist.

Centered on this vision, in this talk I will introduce new imaging and detection architectures that can compensate in the digital domain for the lack of complexity of optical components by use of novel theories and numerical algorithms to address the immediate needs and requirements of Telemedicine for Global Health Problems. Specifically, I will present an on-chip cytometry and microscopy platform that utilizes cost-effective and compact components to enable digital recognition and 3D microscopic imaging of cells with sub-cellular resolution over a large field of view without the need for any lenses, bulky optical components or coherent sources such as lasers. This incoherent holographic imaging and diagnostic modality has orders of magnitude improved light collection efficiency and is robust to misalignments which eliminates potential imaging artifacts or the need for realignment, making it highly suitable for field use. Applications of this lensfree on-chip microscopy platform to high-throughput imaging and automated counting of whole blood cells, monitoring of HIV+ patients (through CD4 and CD8 T cell counting) and detection of waterborne parasites towards rapid screening of water quality will also be demonstrated. Further, I will discuss lensfree implementations of various other computational imaging modalities on the same platform such as pixel super-resolution imaging, lensfree on-chip tomography, holographic opto-fluidic microscopy/tomography. Finally, I will demonstrate lensfree on-chip imaging of fluorescently labeled cells over an ultra wide field of view of >8 cm2, which could be especially important for rare cell analysis (e.g., detection of circulating tumor cells), as well as for high-throughput screening of DNA/protein micro-arrays.

8858-43, Session 11

Rotation-covariant visual concept detection using steerable Riesz wavelets and bags of visual words

Adrien Depeursinge, Stanford Univ. (United States) and Univ. & Univ. Hospitals of Geneva (HUG) (Switzerland) and Univ. of Applied Sciences Western Switzerland (Switzerland); Antonio Foncubierta-Rodriguez, Univ. of Applied Sciences Western Switzerland (HES–SO) (Switzerland); Henning Müller, Univ. of Applied Sciences Western Switzerland (HES–SO) (Switzerland) and Univ. & Univ. Hospitals of Geneva (HUG) (Switzerland); Dimitri Van de Ville, Ecole Polytechnique Fédérale de Lausanne (Switzerland) and Univ. & Univ. Hospitals of Geneva (HUG) (Switzerland)

Distinct texture classes are often sharing several visual concepts. Texture instances from different classes are sharing regions in the feature hyperspace, which results in ill-defined classification configurations. In this work, we detect rotation-covariant visual concepts using steerable Riesz wavelets and bags of visual words. In a first step, k-means clustering is used to detect visual concepts in the hyperspace of the energies of multiscale N-th order Riesz wavelets. The coordinates of the clusters are used to define linear combinations of the Riesz templates that are corresponding to visual concepts. The visualization of these feature signatures allows verifying the relevance of the concepts modeled. Then, the local orientations of each signature are optimized to maximize their response, which is carried out analytically and can still be expressed as a linear combination of the initial steerable Riesz templates. The texture classes are learned in the feature space composed of the concatenation of the maximum responses of each signature using support vector machines. An experimental evaluation using the Outex_TC_00010 test suite demonstrates the feasibility of the proposed approach. A sufficient number k of clusters is required to model the visual concepts. The importance of rotation-covariance is highlighted using the response of the initial templates for classification.

8858-44, Session 11

Time-frequency, frequency coupling, and electroencephalography signals

Sofia C. Olhede, Univ. College London (United Kingdom)

Time-frequency, frequency coupling, and EEG Signals joint work with Maria Fitzgerald and Hernando Ombao

Electroencephalography signals contain a wealth of structure. This can take the form of complicated and patterned time-frequency structure. We shall discuss two special examples and methods for their understanding; namely the development of analysis methods for EEG from prematurely born infants and the formation of their pain perception, as well as adult EEG signals. Models will be built both in frequency; describing the coupling of complicated frequency behaviours, as well as of temporally localized characteristics.

8858-45, Session 11

Video sampling and reconstruction: a comparison of compressed sensing and phase retrieval reconstruction methods

Yoann Le Montagner, Institut Pasteur (France) and Telecom ParisTech (France); Elsa D. Angelini, Telecom ParisTech (France); Jean-Christophe Olivo-Marin, Institut Pasteur (France)

The theory of compressed sensing (CS) predicts that structured images can be sampled in a compressive manner with very few non-adaptive linear measurements, made in a proper adjacent domain. Here, we investigate the problem of recovering a video signal from a subset of Fourier modulus -- therefore non-linear -- samples, taking advantage of some relevant sparse prior assumptions on the signal of interest. We compare this recovery technique to the usual convex reconstruction method encountered when dealing with linear CS measurements. We present some simulation results obtained on real video sequences coming from biological imaging experiments.

8858-46, Session 11

A fast thresholded multi-channel Landweber algorithm for wavelet-regularized multi-angle deconvolution

Nikhil Chacko, Michael Liebling, Univ. of California, Santa Barbara (United States)

3D deconvolution in optical widefield microscopy aims at recovering optical sections through thick objects. Acquiring data from multiple, mutually-tilted directions helps fill the missing cone of information in the optical transfer function, which normally renders the deconvolution problem particularly ill-posed. Here, we propose a fast-converging iterative deconvolution method for multi-angle deconvolution microscopy. Specifically, we formulate the imaging problem using a filter-bank structure, and present a multi-channel variation of a thresholded Landweber deconvolution algorithm with wavelet-sparsity regularization. Decomposition of the minimization problem into subband-dependent terms ensures fast convergence. We demonstrate the applicability of the algorithm via simulation results.

8858-47, Session 12

Decoding bits from photons on the fly: online image formation for spatiotemporal single-photon imaging

Yue M. Lu, Harvard Univ. (United States)

Resolving individual photons in space and time is the holy grail of optical imaging. In recent years, there have been increasing efforts to develop solid-state sensors with single-photon sensitivity. From a signal processing perspective, it is natural to consider these sensors as spatiotemporal sampling devices of the incident light intensity field. The unknown light field can be reconstructed from the sensor measurements by maximum likelihood estimation. Unlike our previous work where the image formation is done offline, we develop a new online image formation algorithm based on stochastic approximations, which can “decode” the bitstreams from the single-photon sensors in real time. We establish the consistency and convergence rate of the proposed recursive estimation scheme.

8858-48, Session 12

Compressed gated range sensing

Grigorios Tsagkatakis, Foundation for Research and Technology-Hellas (Greece); Arnaud Woiselle, Sagem Défense Sécurité (France); George Tzagkarakis, Commissariat à l’Énergie Atomique (France); Marc Bousquet, Sagem Défense Sécurité (France); Jean Luc Starck, Commissariat à l’Énergie Atomique (France); Panagiotis Tsakalides, Foundation for Research and Technology-Hellas (Greece)

Active Range Gated imaging systems employ an active illumination source, usually a laser, and a camera system in order to generate a 2D depth map. Extracting the 2D depth image of a scene is traditionally achieved by either recording a large number of frames, proportional to the requested depth resolution or by utilizing a pattern for the opening and closing of the gates such that efficient encoding of the signals is achieved. In this work, we propose a CS based sampling and reconstruction approach that requires far less samples while being more robust to environmental effects. Assuming a single laser pulse is reflected by an object, CS based sampling amounts to obtaining measurements via a measurements matrix that encodes the random gating function for every frame and must satisfy the RIP property. In order to introduce prior information into the signal characteristics, such as the power drop caused by the distance, an appropriate dictionary is constructed capturing properties such as depth dependencies and backscatter. As a result, the requested vector will be sparse and will only encode the depth information. Reconstruction of the depth signal is obtained by an l¬1 norm minimization. In order to obtain a realistic performance evaluation, special care is given to the modeling of the system. The depth signals are modeled as delta functions at specific time instances, while the interaction between the photons and the molecules in the atmosphere as well as atmospheric absorption and beam divergence are also modeled.

8858-49, Session 12

Angle-preserving quantized phase embeddings

Petros T. Boufounos, Mitsubishi Electric Research Labs. (United States)

The phase of randomized complex-valued projections of real signals preserves information about the angle, i.e., the correlation, between signals. This information can be exploited to design quantized angle-preserving embeddings, which represent such correlations using a finite bit-rate. These embeddings generalize known results on binary embeddings and 1-bit compressive sensing and reduce the embedding uncertainty given the bit-rate.

8858-50, Session 12

Poisson noise removal with pyramidal multi-scale transforms

Arnaud Woiselle, Sagem Défense Sécurité (France); Jean-Luc Starck, Commissariat à l’Énergie Atomique (France); Jalal M. Fadili, ENSICAEN (France)

In this paper, we introduce a new method to stabilize the variance of multi-scale (MS) decimated transforms. We first use this method to the adaptation of the 3D BeamCurvelet transform to data corrupted with Poisson noise, then demonstrate its efficiency by applying the proposed multi-scale variance stabilizing transform (MS-VST) to the denoising of a simulated cosmological volume.

The MS-VST introduced by Zhang [Anscombe 1948, zhang 2008], stabilizes the variance of the low-pass filtered versions of a signal, and builds the stabilized detailed bands by differences of these scales. This implies that the scales must all have the same size, and can only be applied to undecimated trnsforms. In order to generalize this approach to a wider range of multi-scale representations, we introduce two different yet similar variance stabilizing operators that work respectively in the decimated and undecimated spaces. Then we use them on the low-pass scales of a 3D Meyer wavelet transform, in its pyramidal - hence decimated - form, which is at the core of the BeamCurvelets.

The proposed variance stabilized BeamCurvelets are used to recover the underlying density of a simulated dark matter cosmological volume with low and very low count-rate. This transform is well adapted to the filamentary structure of this kind of data. The results are compared to stabilized isotropic undecimated wavelets, and un-stabilized BeamCurvelets, and finally the stabilized BeamCurvelets are combined with the stabilized wavelets to take advantage of their morphological diversity and get even better results.

8858-51, Session 12

Compressed sensing image construction for the LOFAR Radio Telescope

Hugh Garsden, Jean-Luc Starck, Stéphane Corbel, Commissariat à l’Énergie Atomique (France); Cyril Tasse, SKA South Africa (South Africa)

Traditionally, the CLEAN method has been used to produce images from radio interferometry data.

Compressed Sensing is a promising alternative, and we have implemented it in the software that generates images for the LOFAR Radio Telescope in Europe. I will explain how compressed sensing differs from CLEAN, and the details and issues of implementing compressed sensing for real radio telescope data. Statistical and visual results of image generation using compressed sensing will be shown, and compared to CLEAN. Based on these, future work will be listed and discussed, including implementation plans, testing, efficacy, and use by astronomers in the field.

8858-52, Session 12

Spatio-temporal regularization for combined range and reflectance imaging with high photon efficiency

Ahmed Kirmani, Andrea Colaco, Dongeek Shin, Vivek K. Goyal, Massachusetts Institute of Technology (United States)

Conventional cameras for ordinary photography and for ranging by time-of-flight methods use thousands to millions of detected photons per pixel to form images. Through spatio-temporal regularization achieved with MAP estimation under a wavelet-domain sparsity prior and an inhomogenous Poisson-process likelihood function, we form images with dramatically higher photon efficiency—even as low as one detected photon per pixel. We demonstrate this 1 photon-per-pixel photon efficiency along with sub-pulse-width range resolution in megapixel laser range imaging with practical equipment, and we show the improvement of our integrated processing over post facto denoising.

8858-53, Session 12

Compressive sensing in signal and sampling for MIMO radar

Juan Lopez, Zhijun Qiao, The Univ. of Texas-Pan American (United States)

MIMO radar utilizes the transmission and reflection of multiple independent waveforms to construct an image approximating a target scene. Compressed sensing (CS) techniques such as total variation (TV) minimization and greedy algorithms can permit accurate reconstructions of the target scenes from undersampled data. The success of these CS techniques is largely dependent on the structure of the measurement matrix. A discretized inverse scattering model is used to examine the imaging problem, and in this context the measurement matrix consists of array parameters regarding the geometry of the transmitting and receiving arrays, signal type, and sampling rate. We derive some conditions on these parameters that guarantee the success of these CS reconstruction algorithms. The effect of scene sparsity on reconstruction accuracy is also addressed. Numerical simulations illustrate the success of reconstruction when the array and sampling conditions are satisfied, and we also illustrate erroneous reconstructions when the conditions are not satisfied.

8858-77, Session PWed

Imaging dark matter using sparsity

Francois Lanusse, Adrienne Leonard, Jean-Luc Starck, Commissariat à l'Énergie Atomique (France)

By its very nature dark matter cannot be directly observed and only through its gravitational effects can it be studied. In particular, the study of the small deformations of the shapes of background galaxies due to the presence of dark matter, known as weak lensing effect, has received a lot of attention over the past decade and is at the heart of the future ESA mission Euclid. When the distances and shapes of a large number of galaxies can be measured, the problem of reconstructing a 3D dark matter map can be addressed. However, weak lensing is an integrated effect along the line of sight and recovering the radial position of dark matter halos involves deprojecting the lensing signal from a limited number of noisy galaxy shape and distance measurements. Considering that the 3D dark matter density is sparse in an appropriate wavelet based 3D dictionary, this problem can be seen as an instance of Compressed Sensing and the recovery of a 3D map becomes possible using sparsity regularized inversion techniques. We propose an iterative soft thresholding algorithm to solve a penalized least-squares problem. We present our results on simulated dark matter halos and compare them to existing reconstruction techniques. We show that thanks to our 3D sparsity constraint the quality of the reconstructed maps can be greatly improved.

8858-78, Session PWed

Curvelet-based method for orientation estimation of particles

Jouni J. Takalo, Univ. of Jyväskylä (Finland); Jouni A. Sampo, Lappeenranta Univ. of Technology (Finland); Jussi Timonen, Univ. of Jyväskylä (Finland); Samuli Siltanen, Matti Lassas, Univ. of Helsinki (Finland)

A new method based on the curvelet transform is introduced here for estimating the orientation distribution in two-dimensional images of elongated features (particles). Theoretical aspects of the suitability of this method are discussed and its efficiency is demonstrated with simulated and real images of fibrous systems.

The estimate by this method for an image of known features was demonstrated to be very accurate, and to clearly outperform those by the FFT and structure tensor (ST) methods used here to represent traditional orientation-analysis methods. There was also strong indication that the results of curvelet-based method for images of newsprint and organic nanofibrils were more reliable than the corresponding FFT and ST results.

The curvelet analysis of an image can be made very fast: we estimated and partly demonstrated that such analysis can be implemented so that it only takes few milliseconds. This would allow on-line analysis with about 20 micrometer resolution in a paper machine with a web speed of 20 m/s. It is also evident based on the results reported here that the curvelet method is robust and rather insensitive to noise in the image. This property strengthens its usability in practical applications.

8858-79, Session PWed

Optical coherence tomography noise reduction over learned dictionaries with introduction of complex wavelet for start dictionary

Raheleh Kafieh, Hossein Rabbani, Isfahan Univ. of Medical Sciences (Iran, Islamic Republic of)

Optical coherence tomography (OCT) is a recently established imaging technique to describe different information about the internal structures of an object. The performance of this method is principally similar to ultrasound imaging, except that OCT uses light beams instead of sound profiles. OCT has made its most significant clinical contribution in the field of ophthalmology, where it has become a key diagnostic technology in the areas of retinal diseases and glaucoma. Similar to ultrasound images, OCT suffers from speckle noise which causes erroneous interpretation. In this work, we discuss on application of denoising methods based on dictionary learning. It is not computationally efficient to apply K-SVD on the whole image. Therefore, overlapping patches should be obtained from the original data and a dictionary D can be learned on these patches by the K-SVD algorithm. In this paper we compare conventional (2D-CDL) and double-sparse dictionary learning (2D-DSDL) methods for OCT denoising. We also use 3D dictionary learning method in double-sparse dictionary learning (3D DSDL) and show their superiority on 2D versions. The start dictionary in K-SVD algorithm was redundant DCT, but since the proposed penalty term is a highly non-convex functional, local minimum solutions are likely to happen. Thus, a wise initialization could improve the results of conventional algorithms. In our experiments we started with complex wavelet dictionaries for their shift invariant and directionally selective characteristics, along with overcomplete subband decomposition (2D-CWDL and 3D-CWDL).

8858-80, Session PWed

Dense grid sibling frames with linear phase filters

Farras Abdelnour, Weill Cornell Medical College (United States)

We propose new dyadic sibling frames (dual frames sharing the same lowpass filter) dyadic with dense time-frequency grid. The resulting limit functions are smooth with higher approximation order. The proposed frame feature redundant highpass filters which are identical within one sample shift.

This leads to wavelets approximating shift-invariance. The filters are FIR and have vanishing moments.

The filters' design steps are simple and use spectral factorization methods. Enhanced denoising performance has been obtained using redundant wavelets (frames). Additionally, sibling frame wavelets lead to smooth limit functions and computationally stable implementation. In this paper we design 5-channel sibling-frame symmetric filterbank ${h_0,h_1,h_2,h_3,h_4 }$ and using ${g_0,g_1,g_2,g_3,g_4 }$

spectral factorization methods. The resulting filters have linear phase and smooth limit functions.

8858-54, Session 13

Hub screening on brain graphs

Alfred O. Hero, Hamed Firouzi, Univ. of Michigan (United States)

``Connectomes" or Brain Graphs have become a very popular way of representing the neurodata. Recent studies show the existence of highly connected hubs in the brain graphs. Motivated by this fact, we apply the existing theory of correlation screening to discover the correlations in brain graphs. We assign a feature vector of hub p-values to a brain graph. The proposed feature vector enables a computationally efficient classifier for healthy versus patient classification. The efficiency of the proposed method is shown by performing experiments on a fMRI dataset.

8858-55, Session 13

Fast algorithms for multiscale analysis on graphs

Mauro Maggioni, Duke Univ. (United States)

We present a novel approach to construct multiscale dictionaries on graphs, which generalize wavelets to these spaces. The elements of these bases and frames are localized in space and frequency in a way analogous to classical wavelets, but where space is given by a graph and frequency is determined by the spectral representations associated with the Laplacian on a graph. The construction of these bases is accomplished by fast algorithms, and the transforms, both forward and backward, are fast as well.

We then discuss applications to compression of functions on graphs, and to regression and machine learning tasks on graphs.

8858-56, Session 13

Iterated two-channel filterbanks on undirected graphs

Akshay Gadde, Sunil K. Narang, Antonio Ortega, The Univ. of Southern California (United States)

In this paper, we propose the construction of iterative two channel wavelet filterbanks on any arbitrary undirected weighted graph. The proposed two-channel filterbanks provide a multiresolution decomposition of any graph signal into succesive lowpass and highpass signals. This work stems from our previous work on the design of critically sampled two-channel filterbanks on bipartite graphs. We use recent results from the theory of sampling bandlimited signals on graphs, which allow us to downsample the output of each channel in two-channel filterbank on a subset of vertices without loss. We describe the properties of these downsampling sets, and the resulting iterated construction of two-channel filterbanks.

8858-57, Session 13

On the interplay between topology and signals supported on graphs

Michael Rabbat, McGill Univ. (Canada)

Recent work has begun to develop a theory for the representation, processing, and approximation of signals supported on graphs. For signals supported on graphs, the eigenvectors of the graph Laplacian play a role analogous to the Fourier transform. We discuss recent results which develop uncertainty principles for signals supported on graphs, focusing on the role of the graph topology. Characteristics of the graph topology which are captured by the Laplacian spectrum and relate to notions of smoothness with respect to signals supported on the graph. We leverage these observations in an algorithm for fitting a graph to data.

8858-58, Session 13

On the sparsity of wavelet coefficients for signals on graphs

David I. Shuman, Benjamin Ricaud, Pierre Vandergheynst, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Over the past decade, a number of new localized, multiscale transforms have been introduced to analyze data residing on weighted graphs. In signal processing tasks such as regularization and compression, much of the power of "classical" wavelets on the real line is derived from their theoretically and empirically proven ability to sparsely represent piecewise-smooth signals, which appear to be locally polynomial at sufficiently small scales. As of yet in the graph setting, there is little mathematical theory relating the sparsity of localized, multiscale transform coefficients to the structures of graph signals and their underlying graphs. In this talk, we begin to empirically and theoretically investigate the question of which classes of signals on graphs are sparsely represented by different localized, multiscale transforms.

8858-59, Session 13

Anomalous cluster detection

Venkatesh Saligrama, Jing Qian, Boston Univ. (United States)

We are interested in deciding whether or not a cluster of nodes, forming a connected component on a graph, exhibit abnormal behavior. The nodes of the graph have random variables associated with them which are i.i.d standard normal under null hypothesis.Under the alternative, the variables of nodes of the anomalous cluster are i.i.d normal with some positive mean and unit variance. The set of arbitrary-shaped connected sub-graphs of a graph is too large for the well-known optimal scan statistic method to apply directly. We present a novel optimization framework that imposes smoothness of graph structures on the scanned cluster of nodes based on the scan statistic method. Specifically, we propose to tradeoff maximizing the scan statistic with minimizing a graph-cut term, which intuitively acts like doing a graph partitioning between the anomalous and normal nodes.

We then provide a model selection framework that allows to choose the cluster with maximum scan statistic value while being connected. Experiments demonstrate the ability of our method to detect arbitrary-shaped connected anomalous clusters on graphs.

8858-60, Session 13

Detecting subgraph structure of a linear dynamical system

Ameya Agaskar, Harvard Univ. (United States) and MIT Lincoln Lab. (United States); Yue M. Lu, Harvard Univ. (United States)

We consider the problem of detecting hidden graph structure underlying a discrete-time linear dynamical system from only a small set of measurements. We assume that the state space consists of two types of nodes: graph nodes, which obey an autoregressive model driven by Gaussian noise and whose dynamics are determined by an unknown weighted adjacency matrix, and nuisance nodes, whose states are just noise. Our observations are linear combinations of all the nodes' states, determined by an observation matrix that we choose, and further corrupted with measurement noise. We assume that the graph nodes are far outnumbered by the nuisance nodes, and that the number of measurements is limited.

When the observation time is infinite, the graph nodes can be detected and their adjacency matrix reconstructed from the autocovariance computed from the observations. Only the zero- and one-lag covariance matrices are needed. The nullspace of the zero-lag covariance matrix consists of vectors whose support is entirely on the nuisance nodes; by examining these vectors, we can detect the graph nodes. Meanwhile, the adjacency matrix's eigenvalues are the generalized eigenvalues of a matrix pencil formed from these two matrices, and its eigenvectors can be reconstructed from the pencil's generalized eigenvectors. In practice, the observation time is finite and there are errors in estimating the autocovariance matrices. We use results from random matrix theory to determine conditions under which the graph nodes can be effectively distinguished from the nuisance nodes and the bound the error in the estimate of the adjacency matrix.

8858-61, Session 14

Near-optimal phase retrieval of sparse vectors

Afonso S. Bandeira, Princeton Univ. (United States); Dustin G. Mixon, Air Force Institute of Technology (United States); Boris Alexeev, Princeton Univ. (United States)

In many areas of imaging science, it is difficult to measure the phase of linear measurements. As such, one often wishes to reconstruct a signal from intensity measurements, that is, perform phase retrieval.

In several applications the signal in question is believed to be sparse. In this paper, we use ideas from the recently developed polarization method for phase retrieval and provide an algorithm that is guaranteed to recover a sparse signal from a number of phaseless linear measurements that scales linearly with the sparsity of the signal (up to logarithmic factors). This is particularly remarkable since it is known that a certain popular class of convex methods is not able to perform recovery unless the number of measurements scales with the square of the sparsity of the signal.

8858-62, Session 14

Sparsity and compressive sensing with parametric dictionaries

Dian Mo, Marco F. Duarte, Univ. of Massachusetts Amherst (United States)

We discuss the use of sparsity in parametric dictionaries for the purposes of parameter estimation. Common applications include localization and bearing estimation. We also consider the use of such dictionaries in compressive sensing and study sparse recovery algorithms and performance metrics that are tailored to specific applications.

8858-63, Session 14

Equiangular tight frames whose entries are pth roots of unity for small p

John D. Jasper, Univ. of Missouri (United States)

This paper is invited to the Peter Casazza session. In this talk we will present some methods for constructing equiangular tight frames whose entries are pth roots of unity for small p. In particular, we will present an infinite family of equiangular tight frames with all entries in {+1,-1}.

8858-64, Session 14

Frame theory for locally compact abelian groups

Emily J. King, Technische Univ. Berlin (Germany)

Analysis on locally compact abelian groups and local fields has applications in a variety of different fields. Traditional Fourier analysis is based on the characters of R^n, T^n, and Z^n. There is a growing body of literature using functions on p-adic groups to model quantum phenomena, and p-adic wavelets diagonalize certain important pseudo-differential operators. Fourier analysis on local fields comes up class field theory and in the study of particular zeta functions. Piecemeal approaches to classifying shift-invariant spaces and other systems generated by group actions on locally compact abelian groups exist, but a uniform treatment does not yet exist. This talk will present new results in this area.

8858-65, Session 14

Fast null space tuning algorithms with feedbacks for sparse signal recovery

Tiebin Mi, Renmin Univ. of China (China); Shidong Li, San Francisco State Univ. (United States)

We provide another framework of fast iterative algorithms based on null space tuning, thresholding, and feedbacks for sparse signal recovery arising in sparse representation and compressed sensing. Several algorithms with different feedbacks are derived, which are seen as exceedingly effective and fast. Convergence results are also provided. The core algorithm is shown to converge in finite many steps under a (preconditioned) restricted isometry condition. Numerical studies about the effectiveness and the speed of the algorithms are also presented. The algorithms are seen as particularly effective for large scale problems.

8858-66, Session 15

Multiscale dictionaries, transforms, and learning in high-dimensions

Mauro Maggioni, Duke Univ. (United States)

We introduce multiscale constructions for the estimation of the intrinsic dimension of noisy data, the construction of data-driven dictionaries for efficient sparse representations data sets and a novel geometric multiresolution analysis framework for encoding data. Finally we discuss the problem of estimating a probability measure in high dimensions, whose support is (nearly) low-dimensional and has some geometric structure, for example that of a manifold, or a union of hyperplanes. We construct a multiscale geometric tree decomposition of the data and use this decomposition to construct an increasing family of approximation "spaces" in the space or probability measures, parametrized by certain subtrees of the multiscale tree, and perform a multiscale bias-variance tradeoff using this family of approximation spaces. We obtain finite-sample results that guarantee that with high probability the Wasserstein distance between the (random) measure estimated by our algorithm and the true measure is small, depending on the number of samples, a measure of complexity of the models we use (typically this depends only on the intrinsic dimension and not on the ambient dimension!), and a notion of "regularity" of the true measure.

8858-67, Session 15

Random encoding of quantized finite frame expansions

Rayan Saab, Mark Iwen, Duke Univ. (United States)

We address the problem of encoding the bit-stream associated with quantized frame expansions. It has been previously shown that for a wide variety of finite frames, Sigma-Delta quantization achieves much better error decay as a function of the number of frame vectors than simple scalar quantization does. Nevertheless, the known error rates are not optimal. In this talk, we show that there exists a simple, random encoding algorithm acting on Sigma-Delta quantized finite frame expansions which --in conjunction with an associated linear decoding algorithm-- yields an approximation error that decays exponentially in the number of bits used. This result is near optimal, up to constants, and holds for a large family of frames.

More specifically, the proposed encoding strategy consists of applying a discrete random operator to the Sigma-Delta bit stream and assigning a binary codeword to the result. The reconstruction procedure, as previously mentioned, is essentially linear and equivalent to solving a least squares minimization problem. The proof of exponential error decay relies on concentration of measure techniques, subject to the frame at hand satisfying certain properties. In particular, smooth frames and random frames whose elements are sub-Gaussian random variables satisfy these properties.

8858-68, Session 15

Minimal frames for phase retrieval

Yang Wang, Michigan State Univ. (United States)

The classical phase retrieval problem concerns the reconstruction of a function from the magnitude of its Fourier transform. The more general version of it asks whether and how can one reconstruct a signal from the magnitudes of samples of the signal. In this talk we consider various minimality problems on frames with the phase retrieval property. For example, what is the minimal number of vectors needed in a frame to have the phrase retrieval property? For complex frames this question remains one of the main unsolved problems in phrase retrieval. But there are many other such problems. The main goal of this talk is a survey of the latest advances in this area.

8858-69, Session 15

Real phase retrieval by projections

Jameson Cahill, Peter G. Casazza, Jesse Peterson, Lindsey M. Woodland, Univ. of Missouri-Columbia (United States)

Frame theory has broad application today to a wide range of research topics. Integer frames are frames for which all of the entries with respect to a fixed orthonormal basis are integers. Integer frames give promise for reducing calculation times as well as reducing quantization errors. In this paper we make the first detailed study of real integer frames. We will see that equal norm or tight integer frames with N-elements are easy to construct for all M-dimensional Hilbert spaces. We then concentrate on equal norm tight integer frames. We will see that in some cases they cannot exist, such as any odd number of vectors in 2 dimensions. We will also see cases where they exist for all large number of vectors in certain dimensions and we look at some general classes where they exist.

8858-70, Session 16

Reconstruction with diffeomorphic motion compensation for undersampled dynamic MRI

Ganesh Adluru, Edward V. R. DiBella, The Univ. of Utah (United States)

We propose a compressed sensing type of reconstruction method that can handle large amounts of inter-frame motion by including diffeomorphic model-based registration steps within the iterative reconstruction. The method is ideal for speeding up respiratory-navigated late gadolinium enhancement images of the left atrium. It is also suitable for application to a newly proposed type of myocardial perfusion imaging that does not use ECG gating. Such an acquisition is a simpler alternative to conventional ECG gated acquisitions but requires severe undersampling of k-space data and more sophisticated reconstruction methods. The new methods and preliminary results will be presented.

8858-71, Session 16

Motion estimation/compensated compressed sensing using patch-based low rank penalty

Huisu Yoon, Jong Chul Ye, KAIST (Korea, Republic of)

In this paper, a novel patch-based signal processing algorithm for motion estimated/compensated compressed sensing dynamic MR imaging that overcomes the limitation of the existing k-t FOCUSS with ME/MC. More specifically, we impose a non-convex patch-based low-rank penalty that exploits self-similarities within the images. This penalty is shown to favor capturing geometric features such as edges rather than reconstructing the background noises. To solve the resulting non-convex optimization problem, we propose a globally convergent concave-convex procedure (CCCP) using convex conjugate, which has closed form solution at each sub-iteration. Experimental results demonstrate that the proposed algorithm outperforms the existing ones.

8858-72, Session 16

Low-rank and sparse matrix decomposition for accelerated dynamic MRI

Ricardo Otazo, Daniel K. Sodickson, New York Univ. Langone Medical Ctr. (United States); Emmanuel J. Candes, Stanford Univ. (United States)

This paper is invited to Dr. Mathews Jacobs session. Low-rank and sparse matrix decomposition (L+S) is proposed in the spirit of compressed sensing to reconstruct undersampled dynamic MRI data sets with separation of background (low-rank) and dynamic (sparse) components. The technique effectively suppresses the background before enforcing sparsity, which improves reconstruction performance, since the remaining images are sparser. In addition to increasing the acceleration capability of dynamic MRI in general, the ability to suppress the background without parametric modeling or image subtraction may be useful for several contrast-enhanced studies. Feasibility of the L+S method is demonstrated on cardiac cine and perfusion data sets and time-resolved contrast-enhanced angiography.

8858-73, Session 16

Joint image reconstruction and motion parameter estimation for free-breathing navigator-gated cardiac MRI

Mehmet Akcakaya, Reza Nezafat, Beth Israel Deaconess Medical Ctr. (United States)

We develop a reconstruction technique for free-breathing cardiac MRI acquisitions with prospective random undersampling and a respiratory navigating (NAV) approach that only gates the central k-space. In these acquisitions, central k-space is acquired within a pre-specified NAV gating window, minimizing motion artifacts. For the randomly undersampled outer k-space, if the NAV signal corresponding to a k-space segment is outside the gating window, the segment is rejected, but not re-acquired. The proposed compressed sensing-based reconstruction algorithm then jointly estimates the motion parameters of the NAV-rejected outer k-space and the image itself. Feasibility of the algorithm is demonstrated in coronary MRI.

8858-74, Session 16

Exploiting local low-rank structure in higher-dimensional MRI applications

Joshua D. Trzasko, Mayo Clinic College of Medicine (United States)

In many clinical MRI applications, not one but a series of images is acquired. Techniques that promote intra- and inter-image sparsity have recently emerged as powerful strategies for accelerating MRI applications; however, sparsity alone cannot always describe the complex relationships that exist between images in these series. In this talk, sparsity, we will discuss the modeling of higher-dimensional MRI signals as matrices and tensors, and why promoting these signals to be low-rank (and, specifically, locally low-rank) can effectively identify and exploit these complex relationships. Example applications including calibrationless parallel and training-free dynamic MRI will be demonstrated.

8858-75, Session 16

Accelerated dynamic MRI using sparse dictionary learning

Mathews Jacob, Univ. of Iowa (United States); Sajan Goud Lingala, The Univ. of Iowa (United States)

We propose a novel sparse dictionary learning frame work to recover dynamic images from under-sampled mea- surements. Unlike the recent low rank schemes, the proposed scheme models the the dynamic signal as a sparse linear combination of temporal basis functions chosen from a large dictionary. Both the basis functions and the sparse coefficients are estimated from the undersampled data. We show that this representation is much more compact com- pared to the low rank models. We also develop an efficient majorize-minimize algorithm to estimate the sparse model coefficients and the dictionary directly from the measured data. A continuation strategy is proposed to be robust to local minima. We compare the proposed scheme against low rank models and demonstrate improved reconstructions in the context of myocardial perfusion imaging in the presence of motion.

8858-76, Session 16

Prospective motion correction for functional MRI using sparsity and Kalman filtering

Daniel S. Weller, Douglas C. Noll, Jeffrey A. Fessler, Univ. of Michigan (United States)

We develop a novel motion estimation and correction method for use during acquisition of functional magnetic resonance imaging time series. We model the changes in image content between frames as sparse, leveraging the image-domain sparsity of the functional activation changes. We combine this sparse residual model with extended Kalman filter-like tracking, and we implement this method efficiently using a combination of variable splitting and the alternating direction method of multipliers. We demonstrate the efficacy of our method on simulated data by comparing temporal correlations of the data corrected prospectively against data corrected only through post-processing.

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8859-1, Session 1

The advanced x-ray spectroscopic imaging observatory (AXSIO)

Jay A. Bookbinder, Smithsonian Astrophysical Observatory (United States); Robert Petre, Andrew F. Ptak, NASA Goddard Space Flight Ctr. (United States); Randall K. Smith, Smithsonian Astrophysical Observatory (United States)

AXSIO will deliver at least 10-50X the effective area of current x-ray telescopes, which in combination with its two focal plane instruments (the imaging X-ray Microcalorimeter Spectrometer and the X-ray Grating Spectrometer) will result in a 100-fold increase in capability over the current generation of instruments for high-res¬olution spectroscopy. AXSIO covers the 0.1 - 12keV energy range, complementing the capabilities of the next generation observatories such as ALMA, LSST, JWST, and 30-m ground-based telescopes These instruments allow AXSIO to accomplish most of the IXO science goals at a significantly reduced complexity and cost. These capabilities will enable studies of a broad range of scientific questions such as what happens close to a black hole, how supermassive black holes grow, how large scale structure forms, and what are the connections between these processes?

This paper presents an overview of the AXSIO mission science drivers, its capabilities relative to its IXO heritage, its optics and instrument options, the status of its technology development programs, and the mission implementation approach.

8859-2, Session 1

Designing the AXSIO microcalorimeter detector focal plane for optimal science return

Randall K. Smith, Harvard-Smithsonian Ctr. for Astrophysics (United States); Simon R. Bandler, NASA Goddard Space Flight Ctr. (United States); Jay A. Bookbinder, Harvard-Smithsonian Ctr. for Astrophysics (United States); Richard L. Kelley, Robert Petre, Andrew F. Ptak, Stephen J. Smith, NASA Goddard Space Flight Ctr. (United States)

Recent advances in X-ray microcalorimeters enable a wide range of possible focal plane designs for the X-ray Microcalorimeter Spectrometer (XMS) instrument on the future Advanced X-ray Spectroscopic Imaging Observatory (AXSIO). Small pixel designs (<100 um) allow for oversampling of the PSF that enable observations at both high count rates and high energy resolution. Pixel designs utilizing multiple absorbers attached to single transition-edge sensors can extend the focal plane to cover a significantly larger field of view, albeit at a cost in maximum count rate and energy resolution. We have optimized the focal plane with respect to likely targets, mirror and aperture size, focal plane complexity, and technology readiness, and will present the design, along with suggestions towards the key technology developments that will be needed for the AXSIO mission.

8859-4, Session 1

The development of µROSI: micro roentgen satellite instrument

Lars Tiedemann, Elias Breunig, Maria Fürmetz, Walter Kink, Peter Predehl, Max-Planck-Institut für Extraterrestrische Physik (Germany)

The µROSI miniature x-ray telescope is the first x-ray telescope specifically designed for an amateur micro satellite. Its mission is to perform an all-sky survey in the soft x-ray band on board the Italian satellite Max-Valier. Due to the limitations imposed by the small size of the spacecraft, the instrument features a silicon drift detector (SDD) with very low power consumption and a focusing optics that consists of 12 nesting mirror shells. With a field of view of 1° µROSI will perform an all-sky survey flying in sun-synchronous orbit (SSO).

This paper describes the overall telescope design and gives an overview of all major components and subsystems. All subsystems have been tested with flight-like engineering models. The results of these tests are presented in this paper.

The silicon drift detector of the µROSI telescope has been tested with a breadboard electronics and the engineering model of the electronics is currently being manufactured.

One demonstrator mirror shell has been produced and tested in the PANTER x-ray test facility to verify the X-ray properties.

A structural qualification model has been built and tested with mass dummies. It showed sufficient load capability to sinusoidal, random vibration and shock loads.

One key element of the thermal control subsystem for the detector is a latent cold storage which operates at -16°C to guarantee an optimal operating temperature for the SDD. The selected phase change material has been tested successfully in a vacuum chamber.

8859-5, Session 1

Novel space communication technology based on x-ray photons

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Radio frequency(RF) communication has been used in space satellite communications for decades and is still the workhorse for current space projects. Laser based optical communication is a hot topic recently because of its good security, relatively higher data rate, and small antenna size. However, bottlenecks such as the limited transmission distance, the wavelength dispersion during the transmission and mass SWAP burden (size, weight and power) on spacecraft are still major challenges, which restricts the future applications in deep space. A novel space communication method is presented in this paper based on X-ray photons. As a result of X-ray's short wavelength and great penetrability, a communication technology of long distance signal transmission in space can be achieved with smaller volume, lower weight and lower power. Therefore, X-ray communication (XCOM) is especially valuable to the deep space missions, which will be able to realize higher data rates, smaller SWAP than with RF and laser communications. High-speed modulation and high-sensitivity detection of X-rays are two major technical issues for the X-ray communication. A Grid-controlled Modulated X-ray tube (GMXT) is proposed and developed as X-ray transmitter. The communication signal is coded and applied to the modulated grid electrode, and then the corresponding X-ray signals are generated and sent out. X-ray detector based on micro-channel plate(MCP) is used as communication receiver because of its high temporal resolution. An audio communication experiment system based on XCOM is successfully demonstrated in laboratory including the X-ray transmitter and the receiver. The communication speed reaches 64 kilobits per second in a vacuum tube of 6 meters long. As a new concept of space communication, X-ray communication will have more important scientific significance and application prospects when technologies for X-ray modulation and detection are further developed.

8859-6, Session 2

A small mission featuring an imaging x-ray polarimeter with high sensitivity

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We present a detailed description of a small mission capable of obtaining high precision and meaningful measurement of the X-ray polarization of a variety of different classes of cosmic X-ray sources. Compared to other ideas that have been suggested this experiment has demonstrated in the laboratory a number of extremely important features relevant to the ultimate selection of such a mission by a funding agency. The most important of these questions are: 1) Have you demonstrated the sensitivity to a polarized beam at the energies of interest (i.e. the energies which represent the majority (not the minority) of detected photons from the X-ray source of interest? 2) Have you demonstrated that the device's sensitivity to an unpolarized beam is really negligible and/or quantified the impact of any systematic effects upon actual measurements? We present our answers to these questions backed up by laboratory measurements and give an overview of the mission.

8859-8, Session 2

Plans for the next grape balloon flight

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The Gamma RAy Polarimeter Experiment (GRAPE) was first flown on a 26-hour balloon flight in the fall of 2011. GRAPE consists of an array of Compton polarimeter modules (based on traditional scintillation technologies) designed to operate in the energy range from 50 keV up to 500 keV. The ultimate goal of our program is to operate GRAPE in a wide FoV configuration for the study of gamma-ray bursts. For the first balloon flight, GRAPE was configured in a collimated mode to facilitate observations of known point sources. The Crab nebula/pulsar, the active Sun, and Cygnus X-1 were the primary targets for the first flight. Although the Crab was detected, the polarization sensitivity was worse than expected, in part because of a lower-than-expected altitude for much of the flight. Only upper limits on the Crab polarization were obtained. This paper will review the plans for the next GRAPE balloon flight, which is scheduled to take place in the fall of 2014 from Ft. Sumner, NM. These plans involve several modifications designed to improve the polarization sensitivity. These modifications include an expansion of the array of polarimeter modules from 16 to 24 and improvements to the instrument shielding. Sensitivity estimates of the resulting instrument, based on GEANT4 simulations, will be presented.

8859-9, Session 2

Scintillator gamma-ray detectors with silicon photomultiplier readouts for high-energy astronomy

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Space-based gamma-ray detectors for high-energy astronomy face strict constraints of mass, volume, and power, and must endure harsh operating environments. Scintillator materials have a long history of successful operation under these conditions, and new materials offer greatly improved performance in terms of efficiency, time response, and energy resolution. The use of scintillators in space remains constrained, however, by the mass, volume, and fragility of the associated light readout device, typically a vacuum photomultiplier tube (PMT). Recently developed silicon photomultipliers (SiPMs) offer gains and efficiencies similar to those of PMTs, but with greatly reduced mass and volume, high ruggedness, and no high-voltage requirements. We have therefore been investigating the use of SiPM readouts for scintillator gamma-ray detectors, with an emphasis on their suitability for space- and balloon-based instruments for high-energy astronomy. We present our most recent results, including spectroscopy and timing measurements for lanthanum bromide scintillators with SiPM readouts, pulse-shape discrimination using organic scintillators with SiPM readouts, and comparison to Monte Carlo simulations of the optical scintillation light collection using Geant4. We also describe potential applications of SiPM readouts to specific high-energy astronomy instrument concepts.

8859-10, Session 3

Progress of the x-ray CCD camera development for the eROSITA telescope

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The eROSITA space telescope is presently developed for the determination of cosmological parameters and the equation of state of dark energy via evolution of clusters of galaxies. It will perform in addition a census of the obscured black hole growth in the Universe. Furthermore, the instrument development was strongly motivated by the intention of a first imaging X-ray all-sky survey above an energy of 2 keV.

eROSITA is scientific payload on the Russian research satellite SRG and the mission duration is scheduled for 7.5 years. The instrument comprises an array of 7 identical and parallel aligned telescopes. The mirror system is of Wolter-I type and the focal plane is equipped with a PNCCD camera for each of the telescopes. This instrumentation permits spectroscopy and imaging of X-rays in the energy band from 0.3 keV to 10 keV with a field of view of 1.0 degree. The camera development is done at the Max-Planck-Institute for extraterrestrial physics and in particular the key component, the PNCCD sensors, have been designed and fabricated at its semiconductor laboratory. All produced devices were tested and the best selected for the eROSITA project.

Based on calculations, simulations, and experimental testing of prototype systems, the flight cameras have been configured. We describe the camera system, its operation on board of the satellite, and the performance. The most recent test results will be presented as well as the status of the instrument development.

8859-11, Session 3

Soft x-ray imager onboard ASTRO-H

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The Soft X-ray Imager, SXI, is an X-ray CCD camera onboard the ASTRO-H satellite to be launched in 2015. ASTRO-H will carry two types of soft X-ray detector and two types of hard X-ray detector. The soft X-ray detectors are the X-ray calorimeter, SXS, and the SXI covering the energy range between 0.3keV and 12keV. The SXS has an excellent energy resolution of 7eV@6keV with a narrow field of view of 3 arcmin square while the SXI has a medium energy resolution of 150eV@6keV with a large field of view of 38 arcmin square. The X-ray mirror will achieve an effective area of 360cm2@6keV. We employ 4 CCDs of P-channel type in back-side configuration with a depletion layer of 200um. The working temperature is to be -110C deg by using two mechanical coolers. The temperature stability is less than 1C deg. We performed the radiation tests for CCDs and ASICs and confirmed that the SXI would properly function through the entire mission life of ASTRO-H. The inside the SXI body is completely isolated from that of the satellite so that we can avoid a possible contamination problem. We employ an optical blocking filter at the top of the SXI as well as the optical blocking layer on the CCD surface. We passed the CDR and will assemble the FM in 2013. We have fixed the on-board software and are now in developing analysis software on the ground. We will report the SXI status and its expected performance in orbit.

8859-12, Session 3

Performance of the x-ray CCD coated with optical blocking layer for SXI onboard ASTRO-H

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We have developed the back-illuminated X-ray CCD camera (BI-CCD) for Soft X-ray Imager (SXI) onboard ASTRO-H. Since the X-ray CCD, especially BI- CCD has a high sensitivity not only for in X-ray but also in both visible light and UV light, X-ray CCD for SXI is directly coated the 100nm thick aluminum on the surface of the CCD in order to block visible light, and we name this aluminum layer OBL (Optical Blocking Layer).

We have developed the prototype CCD for SXI coated with OBL and we have measured the energy resolution, dark current, quantum efficiency(QE), and so on by irradiating the soft X-ray at KEK-PF and the X-ray from 55Fe. We obtained the energy resolution and QE to be150-170eV at 5.9keV and 84% at 0.54keV, respectively. We have also measured the optical transmission of OBL and confirmed the optical transmission of OBL is an order of 10-5 which was the same order of our expected value.

We will show the performance of the proto-type CCD for SXI, mainly focusing on the QE in detail.

8859-13, Session 3

Advancement of readout ASIC for onboard x-ray CCD cameras

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We report on the development and the performance evaluation of the readout ASIC for an onboard X-ray CCD camera. The quick and low-noise readout is essential for the pile-up free imaging spectroscopy with the future highly sensitive telescope. Our goal is the readout noise of 5e- rms at the pixel rate of 1Mpix/sec, which is about 10 times faster than those of the currently working detectors. We had successfully developed a low-noise mixed-signal Application Specific Integrated Circuit (ASIC) as the front-end electronics of SXI (Soft X-ray Imager) onboard the ASTRO-H satellite. The combination of the differential voltage amplifier and the second-order Delta Sigma ADC achieved the input equivalent noise of 30μV (6e- rms assuming the node sensitivity of 5μV/e-) at the pixel rate of 80kpix/sec. The radiation hardened layout design on an epitaxial wafer realized the sufficiently high tolerance for both of the total dose and the single event effect in a low earth orbit. However, the noise performance was limited at the pixel rate higher than 250kpix/sec. Then we have been developing the new ASIC with the fourth-order Delta Sigma modulators to enhance its inherent noise-shaping performance. It consists of four identical circuits that process the CCD signal simultaneously. A 3mm square bare chip will be packed into a 15mm square ceramic package. We present the performance of the ASIC such as the input equivalent noise, integrated non-linearity, effective signal range as well as the results obtained from the integrated test with a fully-depleted P-channel X-ray CCD.

8859-14, Session 3

Modeling contamination migration on the Chandra x-ray observatory ii

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During its first 14 years of operation, the cold (about -60°C) optical blocking filter of the Advanced CCD Imaging Spectrometer (ACIS), aboard the Chandra X-ray Observatory, has accumulated a growing layer of molecular contamination that attenuates low-energy x rays. Over the past few years, the accumulation rate, spatial distribution, and composition may have changed, perhaps partially related to changes in the operating temperature of the ACIS housing. This evolution of the accumulation of the molecular contamination has motivated further analysis of contamination migration on the Chandra X-ray Observatory, particularly within and near the ACIS cavity. To this end, the current study employs a higher-fidelity geometric model of the ACIS cavity, detailed thermal modeling based upon monitored temperature data, and an accordingly refined model of the molecular transport.

8859-15, Session 4

Proton irradiation test to scintillator-directory-coupled CCD onboard FFAST

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FFAST is a large area sky survey mission at hard X-ray region by using a spacecraft formation flying. It consists of two small satellites, a telescope satellite, carrying a multilayer super mirror, and a detector satellite, carrying scintillator-deposited CCDs (SD-CCDs).

SD-CCD is the imaging device which realized sensitivity to 80 keV by pasting up a scintillator on CCD directly. Soft X-ray events are directly detected in the CCD. On the other hand, Hard X-ray events are converted to optical photons by the scintillator and then the CCD detects the photons. We have obtained the spectrum with 109Cd and successfully detected the events originated from the CsI.

For a space use of a CCD, we have to understand aged deterioration of CCD in high radiative environments. In addition, in the case of SD-CCD, we must investigate the influence of radio-activation of a scintillator.

We performed experiments of proton irradiation to the SD-CCD as space environmental tests of cosmic rays.

The SD-CCD is irradiated with the protons with the energy of 100 MeV and neglected for about 150 hours.

As a result, the derived CTI profile of SD-CCD is similarly to ones of XIS/Suzaku and NeXT4 CCD/ASTRO-H.

In contrast, CTIs derived from the data within 4 hours after irradiation is 10 times or more larger than the ones after 150 hours. This may be due to influence of an annealing.

We also report a performance study of SD-CCD, including the detection of scintillation events, before proton irradiation.

8859-16, Session 4

High-resolution soft x-ray spectrometry using the electron-multiplying charge-coupled device (EM-CCD)

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The Electron-Multiplying (EM) CCD shares a similar structure to the CCD except for the additional gain register that multiplies signal before the addition of read-noise, offering sub-electron effective read-noise at high frame-rates.

EM-CCDs were proposed for the dispersive spectrometer on the International X-ray Observatory to bring sub-300eV X-rays above the noise, increasing the science yield. The high-speed, low-noise performance of the EM-CCD brought added advantages of reduced dark current and stray-light per frame, reducing cooling and filtering requirements. To increase grating efficiency, several diffracted spectral orders were co-located and the inherent energy resolution of the detector was required for order separation. Although the spectral resolution of the EM-CCD is degraded by the gain process, it was shown that the EM-CCD could achieve required separation.

The SAXES spectrometer at the Advanced Resonant Spectroscopy Beamline of the SLS (Paul Scherrer Institute) currently uses a CCD, with charge spreading between pixels limiting the spatial resolution to 24um. Through improving the spatial resolution below 5um alongside upgrading the grating, a factor of two energy resolution improvement could theoretically be made. With the high-speed, low-noise performance of the EM-CCD, photon-counting modes could allow the use of centroiding techniques to improve the resolution. Using various centroiding techniques, a spatial resolution of 2um has been achieved experimentally, demonstrating the benefits of this detector technology for soft X-ray spectrometry.

This paper summarises the use of EM-CCDs from our first investigations for IXO through to our latest developments from ground-based testing for synchrotron-research and looks beyond to future possibilities.

8859-17, Session 4

Performance of buried channel MOSFETS in 0.18-µm CMOS image sensors

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Buried channel MOSFETs are typically used as source followers in high performance CCDs due to their lower 1/f noise compared with surface channel devices. In CMOS image sensors the transistors are almost invariably surface channel and exhibit typical 1/f and RTS noise sources. The question we are addressing is whether better noise performance could be achieved by using buried channel devices in CMOS image sensors for space and other imaging science applications. As a part of the development of buried channel CCD process in 0.18 µm CMOS, a number of buried n-channel MOSFETs were designed and manufactured. The I-V and noise characteristics of the transistors are presented and discussed, and compared with standard surface channel devices.

8859-18, Session 4

Characterization of Si hybrid CMOS detectors for use in the soft x-ray band

Zachary Prieskorn, Christopher V. Griffith, Abraham D. Falcone, Stephen D. Bongiorno, David N. Burrows, The Pennsylvania State Univ. (United States)

We report on the characterization of four HAWAII Hybrid Si CMOS detectors developed for use as X-ray detectors as part of a joint program between Penn State University and Teledyne Imaging Sensors. Interpixel capacitive crosstalk (IPC) has been measured for standard H1RG detectors as well as a specially developed H2RG that uses a unique bonding structure. The H2RG shows significant reduction in IPC, as reported by Griffith et al. 2012. Energy resolution at 1.5 & 5.9 keV was measured as well as read noise for each detector. Dark current as a function of temperature is reported from 150 – 210 K. We also estimate dark current figure of merit for each detector.

8859-19, Session 4

First reports on development of new short wavelength (UV, VUV, and EUV) detector arrays incorporating quantum-dot-coated CMOS array

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This work reports on the process development and first results of a 2D CMOS imaging array coated with quantum dots to add deep UV response. The structure of standard silicon detectors limits short wavelength sensitivity to the near UV. Quantum dots are 2-10nm diameter nanoparticles, whose fluorescence wavelength is determined by particle size. The quantum dots absorb incident UV, VUV and EUV light. The emitted fluorescence is a narrow wavelength distribution of visible light to which the underlying silicon detector array is sensitive. The coated detector remains sensitive to visible light and gains increased sensitivity at shorter wavelengths. By coating a standard off-the-shelf silicon detector, large area deep UV detectors are realizable without the

use of high bandgap materials. Initial VUV device testing was conducted at the NIST Synchrotron Ultraviolet Radiation Facility (SURF III) in Gaithersburg MD.

8859-20, Session 4

Superlattice-doped detectors for FUV, EUV, soft x-ray and particle imaging and spectroscopy

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In 1996, scientists studying images from the Extreme UV Imaging Telescope (EIT) discovered burn-in patterns in the CCDs, including a dark grid-shaped pattern caused by long term EUV exposure through a nickel grid proximate to the surface. The damage observed on EIT is typical of silicon detectors exposed to FUV, EUV, and x-ray radiation, in which accumulated damage to the Si-SiO2 interface leads to charging and instabilities of the detector surface. JPL and Alacron have recently demonstrated a high-performance CMOS camera capable of far ultraviolet imaging with high quantum efficiency and exceptional long-term stability. In this paper, we present experimental results and band structure calculations that illuminate the unique properties of superlattice-doped detectors. The stability of superlattice doped detectors is predicted by the insensitivity of the surface band structure to radiation-induced interface traps and confirmed experimentally by long-term exposure of superlattice-doped CMOS imaging arrays to radiation from pulsed excimer lasers. Superlattice doped CMOS imaging arrays, large-format CCDs, electron-multiplied CCDs, and silicon photodiodes have been demonstrated for several FUV and particle imaging and spectroscopy instrument applications.

8859-21, Session 5

Responsivity mapping techniques for the non-positional CCD: the swept charge device CCD236

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The e2v CCD236 is a swept charge device (SCD) designed as a soft X-ray detector, 0.8 keV to 10 keV, and benefits from improvements in design over the previous generation of SCD to allow for increased detector area, a reduction in split X-ray events and improvements to radiation hardness. Being continually clocked and read-out there is no positional information making responsivity variations hard to measure. Due to the small size of previous devices this wasn't as important. With the larger areas of the device, variations in responsivity are possible and could affect scientific output.

This paper describes novel techniques to achieve a responsivity map across the device using masking and XRF, and spot illumination from an organic light-emitting diode (OLED). The results of this technique should allow a deeper understanding of the device sensitivity and allow better data interpretation in SCD applications.

8859-22, Session 5

The gas pixel detector at the focus of an x-ray optics

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X-ray polarimeters at the focus of an X-ray optics, with or without true 2-d imaging capability, have been proposed in many space missions to arrive at the sensitivity requested by astrophysical models.

Here we show the performances of the Gas Pixel Detector as focal plane instrument of one of the two flight models of JET-X mirrors that were supposed to fly aboard the former Spectrum-X Gamma mission. One unit is currently flying on-board SWIFT while three units are still available for future X-ray experiments.

We measured the imaging capability of the GPD by using the same configuration as that routinely used for measuring the Point Spread Function of an optics. We show that most of its characteristics are preserved notwithstanding the inclined penetration in the GPD drift region, we also verified that the position resolution of the detector provides a negligible contribution.

We used a different configuration to place upper limits on the spurious polarization induced by the reflection at grazing incidence that theoretical calculations indicate to be well below practical detection.

Such calibration measurements were carried out at the PANTER X-ray test facility of the Max-Planck-Institut für extraterrestrische Physik.

8859-23, Session 5

Lifetime estimation of a time projection chamber x-ray polarimeter

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The Gravity and Extreme Magnetism Small Explorer (GEMS) Mission X-ray polarimeter Instrument (XPI) was designed to measure the polarization of 23 sources over the course of its 9 month mission. The XPI consists of two telescopes each with a polarimeter assembly at the focus of a grazing incidence mirror. To make sensitive polarization measurements the GEMS Polarimeter Assembly (PA) employed a gas detection system based on a Time Projection Chamber (TPC) technique. Gas detectors are inherently at risk of degraded performance arising from contamination from outgassing of internal detector components or due to loss of gas.

This paper describes the design and the materials used to build a prototype of the flight polarimeter with the required GEMS lifetime. We report the results from outgassing measurements of the polarimeter subassemblies and assemblies, enclosure seal tests, life tests, and performance tests that demonstrate that the GEMS lifetime is achievable. Finally we report performance measurements and the lifetime enhancement from the use of a getter.

8859-24, Session 5

Hydrogen cells as narrowband geo-coronal lyman-alpha rejection filters for astrophysical photometry

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The JHU Rocket Group is developing hydrogen cells to act as narrow-band Hydrogen Lyman-alpha rejection filters for ultraviolet detectors. A heated tungsten filament in the cell produces free hydrogen atoms by photodissociation of molecular gas contained in the cell. This creates a high enough optical depth at Lyman-alpha, effectively filtering out incident geo-coronal Lyman-alpha emission. This suppression of geo-coronal light will make possible observations of astrophysical sources into the Far-UV below 1200 angstroms, down to the lithium-fluoride edge at 1040 angstroms. The flux attenuation of the hydrogen cells will be measured in a vacuum monochrometer testbed. The goal is to produce a usable hydrogen cell design to be easily mounted on a detector for photometric observations of astronomical sources in the Far-UV below 1200 angstroms, which has been a region often contaminated by bright geo-coronal Lyman-alpha emission.

8859-25, Session 5

Calibration and flight qualification of FORTIS

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The Johns Hopkins University sounding rocket group has completed the assembly and calibration of the Far-ultraviolet Off Rowland-circle Telescope for Imaging and Spectroscopy (FORTIS); a sounding rocket borne multi-object spectro-telescope designed to provide spectral coverage of up to 43 separate targets in the 900 - 1800 Angstrom bandpass over a 30' x 30' field-of-view. Utilizing an autonomous targeting system coupled to a central imaging channel, FORTIS is capable of selecting the far-UV brightest regions of the target area and acquiring medium resolution (R~400) spectra in redundant dual-order spectroscopic channels with ~40cm^2 of effective area at 1200 Angstroms. The maiden launch of FORTIS is scheduled for May 10, 2013 out of the White Sands Missile Range, targeting the extended spiral galaxy M61 and nearby companion NGC4301. We report on the final flight calibrations and qualifications of the instrument, including the component characterization and the results of environmental testing at Wallops Flight Facility, as well as the early flight science results, if available.

8859-26, Session 5

Radiometric calibration of the SWRI ultraviolet reflectance chamber (SWURC) far-ultraviolet reflectometer

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The Southwest Research Institute Ultraviolet Reflectance Chamber (SwURC) is a highly capable UV reflectometer chamber and data acquisition system designed to provide bidirectional scattering data of various surfaces and materials. The chamber provides laboratory-based UV reflectance measurements of water frost/ice, lunar soils, simulants, and analogs to support interpretation of UV reflectance data from the Lyman Alpha Mapping Project (LAMP) Lunar Reconnaissance Orbiter (LRO). A deuterium lamp illuminates a monochromator with a nominal wavelength range of 115 nm to 210 nm. The detector scans emission angles -85° to +85° in the principal plane. Liquid nitrogen passed through the sample mount enables constant refrigeration of tray temperatures down to 78 K to form water ice and other volatile samples. The SwURC can be configured to examine a wide range of samples and materials through the use of custom removable sample trays, connectors, and holders. Calibration reference standard measurements reported here include Al/MgF2 coated mirrors for specular reflection and Fluorilon for diffuse reflectances. This calibration work is a precursor to reports of experiments measuring the far-UV reflectance of water frost, lunar simulants, and Apollo soil sample 10084 in support of LRO-LAMP.

8859-27, Session 6

Characterization, modeling, and management of the COS FUV detector lifetime

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The Far Ultraviolet (FUV) detector of the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (HST) uses a large-format, two-segment microchannel plate detector with a Cross Delay-Line anode. Since the installation of COS into HST in 2009, the detector's properties have continually evolved, and changes to both sensitivity and microchannel plate gain have been observed.

In order to maximize the lifetime of the detector, we have been monitoring its local properties as a function of time, cumulative exposure, and other factors, and we have constructed models to predict its future evolution. These models will allow us to actively manage the microchannel plate high voltage levels and the location of the spectra on the detector in order to extend its life without limiting its scientific use.

We are also tracking the global sensitivity of the detector, which has been decreasing since installation; the rate of degradation has been found to vary with time, and appears to be correlated with solar activity.

We will discuss our progress in extending the life of the detector, with a focus on the results since July 2012, when the spectra were move to a second lifetime position.

8859-28, Session 6

Performance results from in-flight commissioning of the Juno ultraviolet spectrograph (Juno-UVS)

Thomas K. Greathouse, G. Randall Gladstone, Michael W. Davis, David C. Slater, Maarten H. Versteeg, Kristian B. Persson, Brandon C. Walther, Gregory S. Winters, Steven C. Persyn, John S. Eterno, Southwest Research Institute (United States)

We present a description of the Juno ultraviolet spectrograph (Juno-UVS) and results from its in-flight commissioning performed between December 5th and 13th 2011 and its first periodic maintenance between October 10th and 12th 2012. Juno-UVS is a modest power (9.0 W) ultraviolet spectrograph based on the Alice instruments now in flight aboard the European Space Agency's Rosetta spacecraft and NASA's New Horizons spacecraft, and the LAMP instrument aboard

NASA's Lunar Reconnaissance Orbiter. However, unlike the other Alice spectrographs, Juno-UVS sits aboard a spin stabilized spacecraft. The Juno-UVS scan mirror allows for pointing of the slit approximately ±30° from the spacecraft spin plane. This ability gives Juno-UVS access to half the sky at any given spacecraft orientation. The planned 2 rpm spin rate for the primary mission results in integration times per 0.2° spatial resolution element per spin of only ~17 ms. Thus, for calibration purposes, data were retrieved from many spins and then remapped and co-added to build up exposure times on bright stars to measure the effective area, spatial resolution, scan mirror pointing positions, etc. The primary job of Juno-UVS will be to characterize Jupiter's UV auroral emissions and relate them to in-situ particle measurements. The ability to point the slit will make operations more flexible, allowing Juno-UVS to observe the atmospheric footprints of magnetic field lines through which Juno flies, giving a direct connection between energetic particle measurements on the spacecraft and the far-ultraviolet emissions produced by Jupiter's atmosphere in response to those particles.

8859-30, Session 6

An improved wide-field camera for imaging Earth's plasmasphere at 30.4 nm

Michael W. Davis, G. Randall Gladstone, Jerry Goldstein, Southwest Research Institute (United States); Bill R. Sandel, The Univ. of Arizona (United States); Thomas K. Greathouse, Kurt D. Retherford, Gregory S. Winters, Southwest Research Institute (United States)

The Extreme Ultraviolet Imager (EUV) aboard NASA's IMAGE mission studied the distribution of singly ionized helium (He+) in the Earth's plasmasphere by imaging its emission at 30.4 nm. This instrument consisted of three separate camera heads, each with a 28° field-of-view, with 0.6° resolution. We described an improved imaging system that can simultaneously image a 40° field-of-view with 0.45° resolution utilizing only one camera head. This imager also increases throughput over the heritage EUV imager by a factor of four due to improvements in optical coatings, detector technology, and a larger entrance aperture.

8859-31, Session 7

Adaptive digital pulse shaping methods for image readout on the Jupiter ultraviolet dynamic explorer instrument of the ESA juice spacecraft

Steven A. Leach, Jon S. Lapington, Univ. of Leicester (United Kingdom)

A high speed low noise detector signal shaping scheme is under development for application in the proposed Jupiter Ultraviolet Dynamic Explorer (JUDE) instrument for the ESA led Jupiter Icy Moons Explorer (JUICE) mission.

The proposed system will facilitate the UV science objectives of JUICE; Auroral imaging and FUV spectroscopy. JUDE will directly view each hemisphere of Jupiter in addition to separately imaging the Europa, Callisto and Ganymede moons, requiring a combination of high dynamic range and high spatial resolution. A main objective is to develop a radiation tolerant imager that can adapt to these different luminosity conditions with flexibility to optimise the image spatial resolution against the photon event rate.

The JUDE instrument system proposes Microchannel Plate detectors (MCP) coupled with a novel image readout, the Capacitive Division Image Readout (C-DIR). The readout requires four charge measurement channels comprising low noise Charge Sensitive Preamplifiers (CSP) and fast signal conditioning amplifiers. The fast signal from each channel is captured and digitised before application of adaptive digital pulse shaping and peak detection algorithms.

Our experimental setup comprises a low noise analogue frontend electronics unit coupled to a four channel fast digitiser which allows analysis of various digital shaping methods and assessment of their adaptability; their electronic noise performance versus photon event rate trade-off envelope.

This paper presents a comparison of results from digitally coded Moving Window Deconvolution (MWD) and Semi-Gaussian shaping techniques with adjustable parameters to assess their adaptability to the changing photon count rates predicted for the different Jupiter mission phases.

8859-32, Session 7

The capacitive division image readout; a novel imaging device for microchannel plate detectors

Jon S. Lapington, Steven A. Leach, Univ. of Leicester (United Kingdom); Thomas Conneely, Photek Ltd. (United Kingdom)

The Capacitive Division Image Readout (C-DIR) is a simple and novel image readout for photon counting detectors with major performance advantages. C-DIR is a charge centroiding device comprising three elements; (i) a resistive anode providing event charge localization, event current return path and electrical isolation from detector high voltage, (ii) a dielectric substrate which capacitively couples the event transient signal to the third element, (iii) the readout device; an array of capacitively coupled electrodes which divides the signal among the readout charge measurement nodes.

The resistive anode and dielectric substrate constitute the rear interface of the detector and capacitively couple the signal to the external C-DIR readout device. The C-DIR device is a passive, multilayer printed circuit board type device comprising a matrix of isolated electrodes whose geometries define the capacitive network. C-DIR is manufactured using conventional PCB geometries and is straightforward and economical to construct.

C-DIR's robustness and simplicity belie its performance advantages. Its capacitive nature avoids partition noise, the Poisson noise associated with collection of discrete charges. The dominant noise limiting position resolution is electronic noise. However C-DIR also presents a low input capacitance to the readout electronics, minimising this noise component thus maximising spatial resolution. Optimisation of the C-DIR pattern-edge geometry can provide ~90% linear dynamic range.

We present image resolution and linearity measurements of the C-DIR device with microchannel plate detectors and describe various electronic charge measurement scheme designed to exploit the full performance potential of the C-DIR device.

8859-33, Session 7

Opaque gallium nitride photocathodes in UV imaging detectors with microchannel plates

Anton S. Tremsin, Jeffrey S. Hull, Oswald H. Siegmund, Jason B. McPhate, Univ. of California, Berkeley (United States); Amir M. Dabiran, SVT Associates, Inc. (United States)

The recent progress in the development of novel Microchannel Plates (MCPs) manufactured with the help of the Atomic Layer Deposition technology broadens the range of temperatures which are available for the MCP processing, in particular during the photocathode deposition. At the same time, the surface on which the photocathodes are deposited can be modified for a better compatibility with the good quality films grown directly on top surface of the MCP, serving as opaque photocathodes. The opaque photocathodes have generally shown better efficiency compared to the semitransparent configuration even on the flat substrates as there is no compromise need to be found between the depth of absorption and the escape length for the photoelectrons. In case of MCP photocathodes the improvement of detection efficiency can be expected from the fact that photocathode deposited inside the pores is illuminated at a grazing angle and thus photoelectrons are produced closer to the surface and have only short range to travel in order to create an electron avalanche.

8859-34, Session 7

Performance characteristics of atomic layer functionalized microchannel plates

Oswald H. Siegmund, Jason B. McPhate, Univ. of California, Berkeley (United States)

A new method of fabricating microchannel plates has been investigated, employing microcapillary arrays of borosilicate glass that are deposited with resistive and secondary emissive layers using atomic layer deposition. Microchannel plates of this kind have been made in sizes from 33 mm to 200 mm, with pore sizes of 10 µm and 20 µm, pore length to diameter ratios of 80:1, bias angles of 8°, and open areas from 60% to 83%. Tests with single MCPs and MCP pairs have been done and show good imaging quality, gain comparable to conventional MCPs, low background rates (~ 0.085 events sec-1 cm-2), fast pulse response, and good ageing characteristics. The quantum efficiency for bare and alkali halide coated MCPs is similar to conventional MCPs, and we have also been able to deposit opaque GaN(Mg) cathodes directly onto these MCPs.

8859-36, Session 8

The DXL and storm sounding rocket mission

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The objective of the Diffuse X-ray emission from the Local Galaxy (DXL) sounding rocket experiment is to distinguish the soft X-ray emission from the Local Hot Bubble (LHB) from that produced via Solar Wind Charge eXchange (SWCX). Enhanced interplanetary helium density in the helium focusing cone provides a spatial variation to the SWCX that can be identified by scanning through the focusing cone using an X-ray instrument with a large grasp. DXL consists of two large proportional counters refurbished from the Aerobee-IV payload used during the Wisconsin All Sky Survey. The counters utilize P-10 fill gas and are covered by a thin Formvar window (with Cyasorb UV-24 additive) supported on a nickel mesh. DXL's large grasp is 10 cm? sr for both the ? and ? keV bands. DXL was successfully launched from White Sands Missile Range, New Mexico on December 12, 2012 using a Mk70 Black Brant IX sounding rocket.

The Sheath Transport Observer for the Redistribution of Mass (STORM) instrument is a prototype soft X-ray camera also successfully flown on the DXL sounding rocket. STORM uses newly developed slumped micropore ("lobster eye") optics to focus X-rays onto a position sensitize chevron configuration microchannel plate detector. The slumped micropore optics have a 75 cm curvature radius, a collecting area of 32 cm?, and a polyimide/aluminum filter bonded to its surface. STORM's large field-of-view makes it ideal for imaging SWCX with exospheric hydrogen for future missions. STORM represents the first flight of lobster-eye optics in space.

8859-37, Session 8

Flight performance and first results from the sub-orbital local interstellar cloud experiment (SLICE)

Kevin France, Nicholas Nell, Robert Kane, Univ. of Colorado at Boulder (United States); Matthew Beasley, Planetary Resources, Inc. (United States); Eric B. Burgh, Univ. of Colorado at Boulder (United States); Keri Hoadley, Christopher Moore, James C. Green, Univ. of Colorado at Boulder (United States)

We present the flight performance and preliminary science results from the first flight of the Sub-Orbital Local Interstellar Cloud Experiment (SLICE). SLICE is a rocket-borne far-ultraviolet instrument designed to study the diffuse interstellar medium. The SLICE payload comprises a Cassegrain telescope with LiF-coated aluminum optics feeding a Rowland Circle spectrograph operating at medium resolution (R ~ 6000) over the 102 – 107 nm bandpass. The details of the instrument design and calibration are presented in a companion proceeding; we focus on first results from the spring 2013 launch of SLICE in this work. SLICE was launched aboard a Terrier-Black Brant IX sounding rocket from White Sands Missile Range to observe four hot stars sampling different interstellar sightlines. The instrument acquired approximately 300 seconds of on-target time for the primary science targets. We observe atomic and molecular transitions (HI, OI, CII, H2) tracing a range of temperatures, ionization states, and molecular fractions in diffuse interstellar clouds. Initial spectral synthesis results and future plans are discussed.

8859-38, Session 8

The OGRESS sounding rocket payload

Thomas D. Rogers, Univ. of Colorado at Boulder (United States); Randall McEntaffer, Ted Schultz, The Univ. of Iowa (United States); Benjamin R. Zeiger, NASA Goddard Space Flight Ctr. (United States); Phillip H. Oakley, Massachusetts Institute of Technology (United States); Webster Cash, Univ. of Colorado at Boulder (United States)

We present an overview of the OGRESS (Off-plane Grating Rocket for Extended Source Spectroscopy) sounding rocket payload based at the University of Colorado and the University of Iowa. OGRESS is designed to perform high resolution (R ~ 50-100) spectroscopy of diffuse celestial x-ray sources between 0.1 – 1 keV. A wire grid collimator constrains light from diffuse sources into a converging beam that feeds an array of diffraction gratings in the extreme off-plane mount. The spectrum is focused onto GEM (Gaseous Electron Multiplier) detectors. OGRESS is the first payload to use GEMs for space-born applications. Thus, we intend to increase the flight readiness of GEMs to TRL-6, for potential use on future orbital missions. Scheduled to launch in 2014, OGRESS will obtain accurate physical diagnostics of the Vela supernova remnant.

8859-29, Session PMon

The optomechanical design of the sub-orbital local interstellar cloud experiment (SLICE)

Robert Kane, Nicholas Nell, Univ. of Colorado at Boulder (United States); Ted Schultz, The Univ. of Iowa (United States); Kevin France, Univ. of Colorado at Boulder (United States); Matthew Beasley, Planetary Resources, Inc. (United States); Eric B. Burgh, Ames Research Ctr. (United States); Rachel Bushinsky, Keri Hoadley, Univ. of Colorado at Boulder (United States)

We present the fabrication and testing of the Sub-orbital Local Interstellar Cloud Experiment (SLICE), a rocket-borne payload for ultraviolet astrophysics in the 1020 to 1070 Å bandpass. The SLICE optical system is comprised of an ultraviolet-optimized telescope feeding a Rowland Circle spectrograph. The telescope is an 8-inch Cassegrain operating at f/7, with Al optics overcoated with LiF for enhanced far-ultraviolet reflectivity. The holographically ruled grating focuses light at an open-faced microchannel plate detector employing an opaque RbBr photocathode. In this proceeding, we describe the design trades and calibration issues confronted during the build-up of this payload. We place particular emphasis on the technical details of the design, modifications, construction and alignment procedures for SLICE in order to provide a roadmap for the optimization of future ruggedized experiments for ultraviolet imaging and spectroscopy.

8859-39, Session PMon

The EXCEED mission (Earth-orbiting EUV spectrometer for planets)

Ichiro Yoshikawa, The Univ. of Tokyo (Japan)

An earth-orbiting Extreme Ultraviolet spectroscopic mission, EXtreme ultraviolet spectrosCope for ExosphEric Dynamics explore (EXCEED) is ready for the launch (2013 August). The EXCEED mission will carry out out-of-atmosphere observations of Extreme Ultraviolet (EUV: 60-145 nm) emissions from tenuous plasmas around the planets (Mercury, Mars, Venus, Jupiter, and exo-solar planets). In this paper, we will introduce the general mission overview, the instrument, and the scientific targets.

8859-40, Session PMon

Status of the EPIC thin and medium filters on-board XMM-Newton after more than 10 years of operation, Part I: laboratory measurements on back-up filters

Marco Barbera, Univ. degli Studi di Palermo (Italy); Alfonso Collura, INAF - Osservatorio Astronomico di Palermo (Italy); Fabio Gastaldello, INAF - IASF Milano (Italy); Ugo Lo Cicero, INAF - Osservatorio Astronomico di Palermo Giuseppe S. Vaiana (Italy); Nicola La Palombara, INAF - IASF Milano (Italy); Andrea Tiengo, Istituto Univ. di Studi Superiori Pavia (Italy) and INAF - IASF Milano (Italy); Salvatore Varisco, INAF - Osservatorio Astronomico di Palermo Giuseppe S. Vaiana (Italy)

After more than ten years of operation of the EPIC camera on board XMM-Newton we have reviewed the status of its thin and medium filters by performing both laboratory measurements on back-up filters, and analisys of data collected in-flight.

We have selected one thin and one medium back-up filters among those still available in the EPIC consortium, and have investigated their status by laboratory measurements including: UV/VIS transmission measurements, X-ray transmission measurements, IR spectroscopy, and microscopic investigations. We report the results of these measurements and point out some lessons learned for the development and calibration programs of filters for X-ray detectors in future Astronomy missions.

8859-41, Session PMon

Status of the EPIC thin and medium filters on-board XMM-Newton after more than 10 years of operation, Part 2: analysis of in-flight data

Fabio Gastaldello, INAF - IASF Milano (Italy); Marco Barbera, Alfonso Collura, Univ. degli Studi di Palermo (Italy); Ugo Lo Cicero, INAF - Osservatorio Astronomico di Palermo Giuseppe S. Vaiana (Italy); Nicola La Palombara, Nicola Sartore, INAF - IASF Milano (Italy); Andrea Tiengo, Istituto Univ. di Studi Superiori Pavia (Italy) and INAF - Osservatorio Astronomico di Palermo (Italy); Salvatore Varisco, INAF - Osservatorio Astronomico di Palermo Giuseppe S. Vaiana (Italy)

After more than ten years of operation of the EPIC camera on board XMM-Newton we have reviewed the status of its thin and medium filters by performing both analysis of data collected in-flight and laboratory measurements on on-ground back-up filters.

We have investigated the status of the EPIC thin and medium filters by performing an analysis of the optical loading in the PN offset maps to gauge variations in the optical and UV transmission of the filters. We both investigated repeated observations of single optically bright targets and performed a statistical analysis of the extent of loading versus visual magnitude at different epochs. Variations in the X-ray transmission have been investigated by continuous monitoring of the isolated neutron star RXJ 1856-3754 which shows an extremely soft spectrum well modeled by a blackbody with kT of about 60 eV. We report the results of these measurements.

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8860-1, Session 1

Status and overview of the James Webb Space Telescope Observatory *(Invited Paper)*

Mark Clampin, NASA Goddard Space Flight Ctr. (United States)

The James Webb Space Telescope (JWST) is a large aperture (6.5 meter), cryogenic space telescope with a suite of near and mid-infrared instruments covering the wavelength range of 0.6 ?m to 28 ?m. JWST's primary science goal is to detect and characterize the first galaxies. It will also study the assembly of galaxies, star formation, and the formation of evolution of planetary systems. JWST is a segmented mirror telescope operating at ~40K, a temperature achieved by passive cooling of the observatory, via a large, 5-layer membrane-based sunshield. We present an overview of the observatory design and the mission science objectives. With construction of the observatory progressing rapidly across all major observatory systems, we will report on recent highlights such as the completion of all the mirrors in JWST optical chain We will also review the predicted performance of the JWST observatory, based on initial measurements of the telescope optics and instrumentation.

8860-2, Session 1

The James Webb Space Telescope science goals

Jonathan P. Gardner, NASA Goddard Space Flight Ctr. (United States)

The James Webb Space Telescope is the scientific successor to the Hubble and Spitzer Space Telescopes. As a large, cold facility-class space telescope it will address nearly every aspect of astronomy through deep infrared imaging and spectroscopy. The science goals for JWST include the formation of the first stars and galaxies in the early universe; the chemical, morphological and dynamical buildup of galaxies and the formation of stars and planetary systems. Recently, the goals have expanded to include additional studies of dark energy, dark matter, active galactic nuclei, exoplanets and Solar System objects. In this paper, we review the original four science themes and discuss how the scientific output of Webb will extend to these new areas of research.

8860-3, Session 1

Status of the James Webb Space Telescope integrated science instrument module

Matthew A. Greenhouse, NASA Goddard Space Flight Ctr. (United States); Victoria Balzano, Space Telescope Science Institute (United States); Pamela S. Davila, Michael P. Drury, Jamie L. Dunn, Stuart D. Glazer, Ed M. Greville, Gregory I. Henegar, Jason E. Hylan, Ray A. Lundquist, John C. McCloskey, Raymond G. Ohl IV, Robert A. Rashford, Mark F. Voyton, NASA Goddard Space Flight Ctr. (United States)

The Integrated Science Instrument Module (ISIM) of the James Webb Space Telescope (JWST) is discussed from a systems perspective with emphasis on integration & test and overall status to launch. The ISIM is one of three elements that comprise the JWST space vehicle and is the science instrument payload of the JWST. The major subsystems of this flight element and their build status are described.

8860-4, Session 1

Reducing the read noise of the James Webb Space Telescope (JWST) near infrared spectrograph using improved reference sampling and subtraction

Bernard J. Rauscher, NASA Goddard Space Flight Ctr. (United States)

The Near Infrared Spectrograph is the James Webb Space Telescope's (JWST) primary spectrograph. For most observations, NIRSpec is likely to be detector noise limited. A team at NASA Goddard is working to push NIRSpec's H2RG and SIDECAR ASIC-based detector system toward the ultimate noise floor that is achievable with the hardware. In this talk, we describe the overall Improved Reference Sampling and Subtraction (IRS^2) formalism, the detailed characterization that was done to enable it, and the noise results that have been achieved so far. These include total noise less than 6 electrons rms per 1000 second science exposure using 88 up-the-ramp non-destructive reads.

IRS^2 differs from conventional H2RG readout in that the clocking pattern interleaves reference pixels and regular pixels throughout the readout much more extensively than if the pixels were to be readout in their physical order. The reference output, the additional interleaved reference pixels, and blanked off real pixels used as references are all included in a Principal Components Analysis which givens an eigensystem that can be used to treat the noise as linearly independent noise components. This differs from the more traditional approach in astronomy which averages pixels together in the image plane. Knowledge of the eigensystem guides subtraction of the reference information using a Wiener-optimal formalism. IRS^2 is results in reference subtraction that is optimal in a least squares sense.

8860-6, Session 2

Engineering specifications for a 4-meter class UVOIR space telescope derived from science requirements

W. Scott Smith, H. Philip Stahl, NASA Marshall Space Flight Ctr. (United States); Marc Postman, Space Telescope Science Institute (United States); William R. Arnold, NASA Marshall Space Flight Ctr. (United States); Charles S. Kirk, ITT Exelis (United States); Ryan M. Bevan, NASA Marshall Space Flight Ctr. (United States)

An advanced large aperture UV, optical, near IR, UVOIR, space telescope is required for the next generation of astrophysics and exoplanet science. As an initial study a 4 meter aperture was chosen as the largest monolithic mirror that can fit in current launch vehicles. The science requirements of proposed exoplanet and astrophysics missions were used to determine the encircled energy, point spread function stability and thermal environment requirements. These requirements then determine the optical wavefront specification for the telescope assembly. The optical wavefront specification becomes the top level of the error budget that is split into various sources that control the structural, thermal and optical design.

8860-7, Session 2

The high-orbit ultraviolet-visible satellite, HORUS

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The High-ORbit Ultraviolet-visible Satellite (HORUS) is a 2.4-meter class space telescope that will conduct a comprehensive and systematic study of the astrophysical processes and environments relevant for the births and life cycles of stars and their planetary systems, to investigate and understand the range of environments, feedback mechanisms, and other factors that most affect the outcome of the star and planet formation process. HORUS will provide 100? greater imaging efficiency and more than 50? greater UV spectroscopic sensitivity than has existed on the Hubble Space Telescope (HST). The HORUS mission will contribute vital information on how solar systems form and whether habitable planets should be common or rare. It also will investigate the structure, evolution, and destiny of galaxies and the universe. This program relies on focused capabilities unique to space that no other planned NASA mission will provide: near-UV/visible (200-1100nm) wide-field, diffraction-limited imaging; and high-sensitivity, high-resolution UV (100-320nm) spectroscopy. From its semi-stable Earth-Sun L2 orbit HORUS will enjoy a stable environment for thermal and pointing control, and long-duration target visibility. The core HORUS design will provide wide field of view imagery and high efficiency point source FUV spectroscopy using a novel combination of spectral selection and field sharing. The HORUS Optical Telescope Assembly (OTA) design makes optimal use of the SALSO capabilities using a three-mirror anastigmatic configuration to provide excellent imagery over a large FOV. The UV/optical Imaging Cameras use two 21k x 21k Focal Plane Arrays (FPAs) consisting of multiple tiled Si CCD elements. The FUV spectrometer uses cross strip anode based MCPs improved from HST-COS technology.

8860-8, Session 2

Experimental characterization of deployable outer barrel assemblies for large space telescopes

Peter A. Warren, Physical Sciences Inc. (United States); Mark J. Silver, MIT Lincoln Lab. (United States); Benjamin J. Dobson Jr., Diverse Systems Engineering (United States); Howard A. MacEwen, Reviresco LLC (United States)

Abstract to be provided upon government approval

8860-9, Session 3

In-space infrastructures: astrophysics and exploration missions synergisms

Howard A. MacEwen, Reviresco LLC (United States)

Although current budget realities (US and international) discourage optimism regarding future development of large spaceborne astronomical telescopes, it is prudent to identify options to leverage other systems and capabilities that may enhance the cost-benefit equation for astronomy, possibly enabling opportunities sooner rather than later. Using a 20 meter UV-Optical-IR (UVOIR) telescope assembled in space and operating in Sun-Earth L2 halo orbit as a primary baseline, this paper will analyze proposed concepts and technologies for human and robotic missions that could present such opportunities and will provide a summary of the opportunities that can be recognized at the current time. The paper will also explore the possibility that a large space telescope system itself could be leveraged to benefit other missions, for example through shared use of ground infrastructure, in-space operational experience, or other forms of collaboration.

Topics to be considered include the following:

• Launch and orbital transfer systems.

• The International Space Station and its orbital neighborhood.

• Advanced robotics and telerobotics.

• In-space servicing, maintenance, and upgrading.

• Human exploration of deep space objects, including asteroids, the Moon, or Mars.

• Commercial operations and missions.

• Modifications to the baseline space telescope concept generated from interactions with other systems.

Possible partners include other offices within NASA itself; international partners such as ESA and JAXA; and commercial concerns seeking to engage in resource extraction, deep space tourism, and so on.

8860-10, Session 3

Advancing toward far-infrared interferometry in space through coordinated international efforts

David T. Leisawitz, NASA Goddard Space Flight Ctr. (United States)

The international far-infrared astrophysics community is eager to follow up Spitzer and Herschel observations with sensitive, high-resolution imaging and spectroscopy, for such measurements are needed to understand merger-driven star formation, AGN, and chemical enrichment in galaxies, star and planetary system formation, and the development and prevalence of water-bearing planets. Through concerted efforts worldwide, the key enabling technologies are maturing. NASA sponsored the SPIRIT Probe and SPECS flagship-class mission concepts during the past decade. Experiments involving interferometry testbeds are

underway in the UK and the US. With new EU Seventh Framework Programme support, the European community is undertaking science definition studies and investing in enabling technology for a future space far-IR interferometry mission. The Japanese balloon-borne far-IR interferometer FITE is ready for its maiden flight, and NASA's BETTII balloon interferometer is under development, with contributions from the UK. This paper reviews recent technical progress, summarizes mission design tradeoffs, and offers a vision for space-based far-IR interferometry involving international collaboration.

8860-11, Session 3

Optical design and adaptive optics for next generation earth observation systems

Vincent Costes, Ctr. National d'Études Spatiales (France)

High resolution optical systems need bigger and bigger telescopes. The design of such telescopes is a key issue for the satellite design. In order to improve the imaging resolution with low impact to the satellite, a great effort must be made to improve the compactness of the telescope.

This paper will describe the comparative study of several compact optical designs. Different apertures, from F/5 to F/20, and different concepts, TMA (Three Mirror Anastigmat), catadioptric concept and Korsch concept have been studied. We will point out advantages and disadvantages of each design.

For a High resolution earth observing system, the Korsch concept is the classic solution. It is interesting to compare it to others concepts and to reconsider the optical design of such a Korsch Telescope taking into account the possibility to implement adaptive optics.

We will show how compact can be a high resolution telescope: a diffraction limited telescope can be less than ten times shorter than its focal length. A constraining consequence of this compactness is the huge increase of the sensitivity factors. The impacts on the optics and on the opto-mechanical tolerances have been analysed. The need to implement active optics raises.

Our analyses and recent developments in adaptive optics technologies will be presented. In particular, our recent studies and developments in lightweight mirrors and in adaptive deformable mirrors will be described.

8860-12, Session 3

Compact infrared camera (CIRC) for earth observation adapting athermal optics

Eri Kato, Haruyoshi Katayama, Masataka Naitoh, Masatomo Harada, Ryoko Nakamura, Ryota Sato, Japan Aerospace Exploration Agency (Japan); Koji Nakau, Hokkaido Univ. (Japan)

We have developed the compact infrared camera (CIRC) with an uncooled infrared array detector (microbolometer) for space application. The main mission of the CIRC is the technology demonstration of the wildfire detection using a large format (640?480) microbolometer. Wildfires are major and chronic disasters affecting numerous countries, especially in the Asia-Pacific region, and may get worse with global warming and climate change.

Microbolometers have an advantage of not requiring cooling systems such an a mechanical cooler, and is suitable for resource-limited sensor systems or small satellites. Main characteristic of the CIRC is also an athermal optics. The athermal optics compensates the defocus due to the temperature change by using Germanium and Chalcogenide glass which have different coefficient of thermal expansion and temperature dependence of refractive index. The CIRC achieves a small size, light weight, and low electrical power by employing the athermal optics and a shutter-less system.

Two CIRCs will be carried as a technology demonstration payload of ALOS-2 and JEM-CALET, which will be launched in JFY 2013 and 2014, respectively. We have finished the ground calibration test of the CIRC Proto Flight Model (PFM). Athermal optical performance of the CIRC have been confirmed by measuring modulation transfer function (MTF) in a vacuum environment and at environmental temperature from -15 to 50 °C. As a result, MTF was found to be effective at capturing clear images across the entire range of operating temperatures. We also provide an overview of the CIRC and radiometric test results in this presentation.

8860-13, Session 3

A small space telescope for large spectroscopic surveys of galaxies

Sara R. Heap, Qian Gong, Lloyd R. Purves, NASA Goddard Space Flight Ctr. (United States); Massimo Robberto, Space Telescope Science Institute (United States); Tony Hull, The Univ. of New Mexico (United States)

One of the goals of NASA's astrophysics program is to answer the question, How did galaxies evolve into the spirals and elliptical galaxies that we see today? This question can be answered by a large spectroscopic survey of galaxies at redshifts, z>1. We will describe our concept for a survey space telescope (~1.5 m) intended for a NASA MidEx mission. It includes a multi-object spectrograph (~500 galaxies per exposure) which has 3 channels to cover the spectral range, 0.2-1.6 microns at a resolving power, R~400. For a redshift z=1 galaxy, these parameters translate to a restframe spectral coverage of 0.1-0.8 microns and R=800. The mission concept takes advantage of two new technological advances: (1) the Digital Micromirror Device (DMD) to be used as a slit selector in a multi-channel (UV, optical, NIR), multi-object slit spectrograph, and (2) light-weighted, wide field of view telescope mirrors.

8860-14, Session 4

Wide-field infrared survey telescope (WFIRST) 2.4-meter mission study *(Invited Paper)*

David A. Content, NASA Goddard Space Flight Ctr. (United States); Laura B. Abplanalp, ITT Exelis (United States); Kevin R. Anderson, Richard W. Capps, Zensheu Chang, Jennifer A. Dooley, Jet Propulsion Lab. (United States); Robert M. Egerman, ITT Exelis (United States); Renaud Goullioud, Daniel B. Klein, Jet Propulsion Lab. (United States); Jeffrey W. Kruk, Mark E. Melton, John A. Ruffa, NASA Goddard Space Flight Ctr. (United States); Michael Underhill, David Van Buren, Jet Propulsion Lab. (United States)

The most recent study of the Wide Field Infrared Survey Telescope (WFIRST) mission is based on reuse of an existing 2.4m telescope. This study was commissioned by NASA to examine the potential science return and cost effectiveness of WFIRST by using this significantly larger aperture telescope. We review the science program envisioned by the WFIRST 2012-2013 Science Definition Team, the telescope design and status, and an overview of the mission concept. Comparisons against the previous 1.3m and reduced cost 1.1m WFIRST design concepts are discussed. A significant departure from past point designs is the option for serviceability and the geostationary orbit location which enables servicing and replacement instrument insertion later during mission life. Other papers at this conference provide more in depth discussion of the wide field instrument and the optional exoplanet imaging coronagraph instrument.

8860-15, Session 4

Wide field instrument preliminary design for the wide field infrared survey telescope

David A. Content, NASA Goddard Space Flight Ctr. (United

States); Nerses V. Armani, SGT, Inc. (United States); Charles L. Baker, John P. Hawk, NASA Goddard Space Flight Ctr. (United States); Clifton E. Jackson, NASA Goddard Space Flight Ctr. (United States) and SGT, Inc. (United States); Duncan M. Kahle, Jeffrey W. Kruk, John P. Lehan, Mark E. Melton, John E. Mentzell, Joseph J. Miko, David J. Palace, Bert A. Pasquale, Hume L. Peabody, NASA Goddard Space Flight Ctr. (United States); Brian S. Smith, Stargazer Systems (United States); Walter F. Smith, Jeffrey W. Stewart, David A. Vaughnn, Thomas E. Wallace, NASA Goddard Space Flight Ctr. (United States)

We present the Wide Field Infra-Red Survey Telescope (WFIRST) instrument concept based on reusing a 2.4m telescope recently made available to NASA. Two instrument channels are described, a wide field channel (~0.8x0.4degrees, 300Mpix), and an integral field unit (3x3 arcsec, 1Mpix, R{2pixel} ~100 over 0.6-2.0um). For this mission concept, the instruments and spacecraft are in a geosynchronous orbit and are designed for serviceability. This instrument can accomplish not only the baseline exoplanet microlensing, dark energy, and infrared surveys for WFIRST, but also can do so at higher angular resolution and with deeper observations, which enables significant opportunities for much more capable general observer programs. The emphasis on achieving very good imaging stability is maintained from the previous work.

8860-16, Session 4

A tolerancing approach taking into account the interferometric alignment scheme of the EUCLID NISP space optics

Frank U. Grupp, Max-Planck-Institut für Extraterrestrische Physik (Germany) and Univ.-Sternwarte München (Germany); Andreas Bode, Max-Planck-Institut für Extraterrestrische Physik (Germany); Eric Pietro, Observatoire Astronomique de Marseille-Provence (France); Ralf Bender, Max-Planck-Institut für Extraterrestrische Physik (Germany) and Univ.-Sternwarte München (Germany)

The ESA-EUCLID space mission has entered phase B2. A new, more advanced tolerancing approach for the NISP near infrared spectrometer and photometer is presented with this paper. The new approach takes into account the interferometric, hologram based and highly accurate alignment scheme as well as the mechanical interface structure of the NISP instrument. Alignment accuracies of <5mu are desired for the mission. A matter unprecedented for large >150mm transmissive space optics.

8860-18, Session 5

Point spread function and photon transfer of a proton-damaged CCD for space-based astronomy

Edgar A. H. Allanwood, The Open Univ. (United Kingdom); Neil J. Murray, e2v Ctr. for Electronic Imaging at The Open Univ. (United Kingdom); David J. Hall, Konstantin D. Stefanov, The Open Univ. (United Kingdom); Andrew D. Holland, e2v Ctr. for Electronic Imaging at The Open Univ. (United Kingdom); David J. Burt, e2v technologies plc (United Kingdom)

The Euclid VISible instrument (VIS) and Near-Infrared Spectrometer-Photometer (NISP) will survey the shapes of galaxies and their red-shifts respectively, to assist in building a three-dimensional map of the Dark Universe. A weak gravitational lensing survey has high requirements, particularly with regard to the stability of the Point Spread Function (PSF) of the imaging system. In this case an array of thirty-six 4k ? 4k pixel e2v CCD273s will be utilised for the focal plane.

A proton-irradiated front-illuminated CCD273 is tested qualitatively, with particular attention paid to spot PSF measurement techniques and single pixel Photon Transfer Curve (PTC) generation under experimental device operating regimes. Variation in ellipticity of the PSF is evaluated against signal level and rate of incoming optical flux. Development of an optical test bench and the subsequent mitigation of systematic errors affecting spot projection consistency are also discussed.

Data is presented for irradiated and un-irradiated regions of a CCD273 with accompanying inferences of the impact of these measurements during the mission.

8860-19, Session 5

OSIRIS-REx OCAMS detector assembly characterization

Jed J. Hancock, Blake G. Crowther, Mitch Whiteley, Robert Burt, Michael Watson, Joel Nelson, Utah State Univ. Research Foundation (United States); Charles W. Fellows, Bashar Rizk, Ellyne K. Kinney-Spano, Marcus L. Perry, Mark R. Hunten, The Univ. of Arizona (United States)

The OSIRIS-Rex asteroid sample return mission carries a suite of three cameras refered to as OCAMS. The Space Dynamics Lab at Utah State University is providing the CCD-based detector assemblies for OCAMS to the Lunar Planetary Lab (LPL) at the University of Arizona . Working with the LPL, SDL has designed the electronics to operate a 1K by 1K frame transfer Teledyne DALSA Multi Pinned Phase (MPP) CCD. The detector assembly electronics provides the CCD clocking, biasing, and digital interface with the OCAMS payload Command Control Module (CCM). A prototype system was built to verify the functionality of the detector assembly design and to characterize the detector system performance at the intended operating temperatures. The characterization results are described in this paper.

8860-20, Session 5

Tri-level parallel clocking of CCDs for: improving charge transfer efficiency, clearing persistence, clocked anti-blooming, and generating low-noise backgrounds for pumping

Neil J. Murray, The Open Univ. (United Kingdom); David J. Burt, e2v technologies plc (United Kingdom); Andrew D. Holland, Konstantin D. Stefanov, Jason P. D. Gow, Calum MacCormick, The Open Univ. (United Kingdom); Mark S. Cropper, Mullard Space Science Lab. (United Kingdom)

A tri-level clocking scheme has been developed to improve the parallel CTE of four-phase CCDs by supressing the effects of traps located in the transport channel under barrier phases by inverting one of these phases throughout the transfer sequence.

In parallel, it was apparent that persistence following optical overload in both Euclid VIS and LSST detectors would lead to undesirable signal released in subsequent rows and frames and that a suitable scheme for flushing this signal would be required. With care, the negatively biased electrodes during the tri-level transfer sequence can be made to pin the entire surface, row-by-row, and annihilate the problematic charges.

This process can also be extended for use during integration to significantly reduce the unusable area of the detector, as per the clocked anti-blooming techniques developed many years ago; however, with the four-phase electrodes architecture of modern CCDs, we can take precautionary measures to avoid the problem of charge pumping and clock induced charge within the science frames.

Clock induced charge is not all bad! We also propose the use of on-orbit trap-pumping for Euclid VIS to provide calibration input to ground based correction algorithms and as such a uniform, low noise background is require. Clock induced charge can be manipulated to provide a very suitable, low signal and noise background to the imaging array.

Here we describe and present results of tri-level parallel clocking schemes for use in four-phase CCDs that could improve performance of high precision astronomy applications such as Euclid VIS and LSST.

8860-21, Session 5

UV/visible detector arrays and coatings for efficient optical systems

Shouleh Nikzad, Michael E. Hoenk, Alexander G. Carver, Todd J. Jones, Timothy M. Goodsall, John Hennessy, April D. Jewell, Jet Propulsion Lab. (United States); Erika T. Hamden, Columbia Univ. (United States)

Ultraviolet detectors and system technologies have received increased attention from all the fields of science and engineering, due to a wide variety of applications in cosmology, wafer inspection, lithography, life detection, planetary atmospheric studies, skin cancer detection, and mineralogy, and astronomy. UV photons interact with the outermost layers of materials, and are therefore highly sensitive to surface effects, including especially surface/interface defects and traps in back-illuminated detectors. Therefore, surface bandstructure modifications and nano-engineered materials are especially important for UV detectors, sensors, optics and instruments. Recent advances in nanotechnology and nano-engineering lead to opportunities to radically improve detector spectral range, sensitivity, and dark noise and system performance. In parallel, new system developments, allow these bandstructure modification to be performed at large scale both in size and in numbers. We will present our latest results achieving high efficiency in various platforms including photon counting (PC), solid-state detector arrays. The high QE achieved are made possible using back illumination and precision interface band engineering of Molecular Beam Epitaxy (MBE) and Atomic Layer Deposition (ALD). Similar concepts and techniques used in achieving higher efficiency optics will also be presented.

8860-22, Session 5

Narrow bandpass steep edge optical filter for the JAST/T80 telescope instrumentation

Steffen Reichel, SCHOTT AG (Germany); Ulf G. Brauneck, SCHOTT Guinchard (Switzerland); Antonio Marín-Franch, Ctr. de Estudios de Física del Cosmos de Aragón (Spain); Sébastien Bourquin, SCHOTT Swiss SA (Switzerland)

The Observatorio Astrofisico de Javalambre in Spain observes with its telescope galaxies in the Local Universe in a systematic study. This is accomplished with a multi-band photometric all sky survey called Javalambre Photometric Local Universe Survey (JPLUS). A wide field camera receives the signals from universe via optical filters. In this presentation the development and design of a narrow bandpass steep edge filter with wide suppression will be shown. The filter has a full width half maximum in the range of 13-15 nm (with <1 nm tolerance) with central wavelengths in the range 350-860nm and an average transmission larger than 90% in the passband. Signals beyond the passband (blocking range) have to be suppressed down to 250nm and up to 1100nm (spectral regime), where a blocking of OD 5 (transmission < 10-5) is required. The edges have to be steep for a small transition width from 5% to 80%. The spectral requirements result in a large number of layers which are deposited with magnetron sputtering. The transmitted wavefront error of the optical filter must be less than lambda/2 over the 100mm aperture and the central wavelength uniformity must be better than +/- 0.4% over the clear aperture. The filter consists of optical filter glass and a coated substrate in order to reach the spectral requirements. The substrate is coated with more than 120 layers. The total filter thickness was specified to be 8.0mm. Results of steep edge narrow bandpass filters will be demonstrated fulfilling all these demanding requirements.

8860-37, Session 5

The relationship between pumped traps and signal loss in buried channel CCDs

Neil J. Murray, Andrew D. Holland, The Open Univ. (United Kingdom); David J. Burt, e2v technologies plc (United Kingdom); David J. Hall, The Open Univ. (United Kingdom)

Pocket-pumping is an established technique for identifying the locations of charge trapping sites within the transport channels of CCDs. Various parameters of the pumping process can be manipulated to increase the efficiency, or allow characterisation of the trap sites effective during nominal operating modes.

A CCD273 was irradiated in a triangular region by protons to a 10 MeV equivalent fluence of 1.2E9 p.cm2, ensuring a suitably low trap density for ease of automated trap recognition. X-rays of 5,898 eV were incident on the CCD above the region irradiated with the triangle, such that events could be analysed having passed through an increasing length of irradiated silicon and hence number of trapping sites.

Here we present the relationship between the number of traps identified by pocket pumping within the parallel transport channels of a CCD273 and the amount of signal that is deferred by the trapping process during readout.

8860-23, Session 6

Radiation damage to five selected optical materials

Reinhard Katterloher, Norbert Geis, Max-Planck-Institut für Extraterrestrische Physik (Germany); Frank U. Grupp, Ralf Bender, Max-Planck-Institut für Extraterrestrische Physik (Germany) and Univ.-Sternwarte München (Germany)

Five optical materials, LF5, LF5G15, S-FTM16, CaF2 and Suprasil 3001are being tested for their radiation hardness in the spectral range between 920nm and 2000nm. Additional information for the VIS spectral range is presented with reduced spectral resolution. The material is radiated with 80 and 10MeV protons in two steps. Total dose (in Si) corresponds to 5 and 10kRad.

8860-24, Session 6

Benefits of ion milling ULE as compared to glass ceramics

Joseph F. Ellison, Gerald P. Cox, Corning Tropel Corp. (United States); Larry J. Sutton, Andrew Fox, Corning Incorporated (United States); Thomas A. Sebring, Xoptx LLC (United States)

Corning's ULE® is an ultra-low expansion glass used for machine tool blocks to astronomical mirrors. Its main competition is a glass ceramic. In many applications, ion beam milling is used for final surface figuring. Ion milling removes material at an atomic level and is typically a slow, expensive process. Experiments have determined the upper limits of removal rate for ion beam milling during optical figuring. The goal was to increase the power density of the ion beam during figuring to achieve higher removal rates with no negative effects on surface properties. Testing results show that the removal rate on ULE® is about 57% higher than on glass ceramic under the same conditions. With an increase in material removal rate, both ULE® and the glass ceramic show an increase in surface roughness, 17% and 24% respectively. Average

birefringence of both materials show a slight increase after milling, 20% for ULE® and 5% for the glass ceramic; however the actual level of birefringence in the glass ceramic is 7 times larger than for ULE®. One unexpected result was as the power was increased, material removal rate for both materials plateaued. This results when ion implantation is balanced by material removal. Angling the sample relative to the incident ion beam will reduce the implantation and further increase material removal. Therefore using higher ion milling power densities, the surface figuring of ULE® can be accelerated to produce shorter processing times. This can help lower the cost for manufacture of ULE® optics.

8860-25, Session 6

ZERODUR®: progress in CTE characterization

Ralf Jedamzik, Clemens Kunisch, Thomas Westerhoff, SCHOTT AG (Germany)

In 2010 SCHOTT introduced a method for the modeling of the thermal expansion behavior of ZERODUR® under arbitrary temperature profiles for an optimized production of material for the upcoming Extremely Large Telescope (ELT) projects. In 2012 a new product was introduced based on this method called ZERODUR® TAILORED. ZERODUR® TAILORED provides an evolution in the specification of the absolute Coefficient of Thermal Expansion (CTE) value by including the individual customer requirements in this process. This paper presents examples showing the benefit of an application oriented approach in the design of specifications using ZERODUR®. Additionally it will be shown how the modeling approach has advanced during the last years to improve the prediction accuracy on long time scales.

ZERODUR® is known not only for its lowest CTE but also for its excellent CTE homogeneity as shown in the past for disc shaped blanks typical for telescope mirror substrates. Additionally this paper presents recent results of CTE homogeneity measurements in the single digit ppb/K range for a rectangular sized plate proving that the excellent CTE homogeneity is independent of the production format.

8860-26, Session 6

Overview and recent accomplishments of the advanced mirror technology development (AMTD) for large aperture UVOIR space telescopes project

H. Philip Stahl, NASA Marshall Space Flight Ctr. (United States)

ASTRO2010 Decadal Survey stated that an advanced large-aperture ultraviolet, optical, near-infrared (UVOIR) telescope is required to enable the next generation of compelling astrophysics and exoplanet science; and, that present technology is not mature enough to affordably build and launch any potential UVOIR mission concept. AMTD is the start of a multiyear effort to develop, demonstrate and mature critical technologies to TRL-6 by 2018 so that a viable flight mission can be proposed to the 2020 Decadal Review. AMTD builds on the state of art (SOA) defined by over 30 years of monolithic & segmented ground & space-telescope mirror technology to mature six key technologies: Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates; Support Systems; Mid/High Spatial Frequency Figure Error Correction; Segment Edges Control; Segment to Segment Gap Phasing; and Integrated Model Validation. AMTD is pursuing multiple design paths to provide the science community with options to enable either large aperture monolithic or segmented mirrors with clear engineering metrics traceable to science requirements. This paper will provide an overview of the study objectives and summarize recent accomplishments.

8860-27, Session PMon

Khayyam: a tunable spatial heterodyne spectrometer for observing diffuse target emission lines

Sona Hosseini, Walter M. Harris, Jason B. Corliss, Univ. of California, Davis (United States)

We describe first-light results from a new instrument-telescope configuration that combines all of the capabilities necessary to obtain high resolving power visible band spectra of diffuse targets from small aperture telescopes where significant observing time can be obtained. This instrument, Khayyam, is a tunable all-reflective spatial heterodyne spectrometer (TSHS) that is mounted to a fixed focal plane shared by the 0.6m Coude auxiliary telescope on Mt. Hamilton, CA. Khayyam has up to 55 arcsec input field of view, resolving power up to 176000, and a tunable bandpass covering >100nm. Khayyam is being field tested to study spatially extended solar system targets where high resolving power is necessary to separate multimodal signals, crowded molecular bands, and to sample low (<10 km/s) velocities at rapid temporal cadence. Here we will discuss the design considerations going into this new system and the initial results of the installation and testing and the future plans.

8860-28, Session PMon

Differential measurement method for atmospheric refraction

Jian-jun Cao, Lixin Zheng, Shanghai Astronomical Observatory (China)

In traditional astronomical observation, it is seldom to observe objects with altitude lower than 15 degree because of the effect of atmospheric refraction. But for the complete theoretical research of the atmospheric refraction, it is necessary to observe such objects, even with the altitude close to 0 degree. Also in the field of monitoring of space targets, some objects at large zenith distance need to be observed. Taking the differential observation principle of Hipparcos astrometric satellite as reference, a new differential method is designed to measure atmospheric refraction: two reflection mirrors with fixed angle that can be rotated accurately are installed in front of the incident light stop of a 20cm telescope, which make it possible to observe two sky regions at one time. First we can determine the practical angle by observing the two sky regions near the zenith. Then the two regions of different altitudes at one azimuth are observed. The atmospheric refraction of low altitude can be calculated by combining the arc length from star catalog coordinates and the practical angle of the mirrors. The differential method is simple relatively and it can improve the ability of monitoring objects at large zenith distance with high precision.

8860-29, Session PMon

Infrared metal mesh bandpass filter supported by ultrathin freestanding polyimide

Bruce M. Lairson, David A. Grove, Heidi C. Lopez, Travis Ayers, Luxel Corp. (United States); Joseph D. Adams, Cornell Univ. (United States)

Metal slot mesh grids can be used to form bandpass filters in the wavelength range from 10 microns to 1000microns. We investigated fabrication of metal-absent slot grids comprised of thin gold on ultrathin freestanding polyimide membranes. Prototype filters were made for evaluation on the SOFIA FORCAST instrument. The filters had peak transmission of up to 87% at a wavelength 30 microns, measured at room temperature, with bandwidths of 25-35%. Fits to the transmission spectra, with the transmission loss attributed to polyimide absorption, yields an extinction coefficient k=0.04, similar to previously reported values in these resonant structures. We discuss the feasibility of this

structure for the construction of dichroic air-gap bandpass filters, with improved rejection and bandpass characteristics, for use in the 10-200micron wavelength range.

8860-30, Session PMon

Elimination of linear astigmatism in off-axis three-mirror telescope and its applications

Seunghyuk Chang, Off-Axis Optics Lab. (Korea, Republic of)

Increasing interest in off-axis reflecting telescopes has been observed recently since their obstruction-free configuration can provide superior optical performance compared to conventional on-axis reflecting telescopes. Linear astigmatism is the dominant field aberration of off-axis reflecting telescopes. It was shown in my previous work [SPIE 626548] that the linear astigmatism can be eliminated in off-axis two-mirror telescope by designing the system to satisfy a closed-form equation. It was also shown that the field of view of a linear-astigmatism-free off-axis two-mirror telescope is equivalent to that of an conventional on-axis telescope. However, in general, a two-mirror telescope has limited field of view due to residual third-order astigmatism and field curvature. Three-mirror design is essential for a wide field telescope since these aberrations can be compensated. In this work, an exact analytic solution for the elimination of linear astigmatism in off-axis three-mirror telescope is presented. Several design examples based on the equation are also presented and compared to the similar designs reported previously.

8860-31, Session PMon

Pixel-level modelling and verification for the EUCLID VIS CCD

Andrew S. Clarke, David J. Hall, Jason P. D. Gow, Neil J. Murray, Andrew D. Holland, The Open Univ. (United Kingdom)

Euclid is an M-class mission selected for the next phase of ESAs long-term cosmic vision programme. The missions primary aim is to provide insight into the physical cause of the accelerating universe which will be achieved by investigating the nature of dark energy, dark matter and gravity. The investigation will involve the measurement of the effects of intervening gravitational potentials on visible light from distant galaxies, a process known as weak gravitational lensing.

The CCD273 was designed by e2v for the Euclid mission, and is based on an older design for the CCD204, with changes designed and implemented to improve operation under irradiation. These changes include a narrower buried channel in the serial register to reduce trap interactions during readout. Pixel level models have been developed to improve knowledge of charge packet distribution within the CCD273 and CCD204 using Silvaco TCAD, enabling predictions to be made about device functionality before and after irradiation which can be immediately tested on both devices.

This paper is focussed on latest results, with particular reference to the on-going model verification, designed to build confidence in the device models and provide feedback to further improve the modelling effort.

8860-32, Session PMon

Calibrating apodizer fabrication techniques for high-contrast coronagraphs on segmented and monolithic space telescopes

Anand Sivaramakrishnan, Space Telescope Science Institute (United States); G. Lawrence Carr, Randy Smith, Xiaoxiang Xi, Brookhaven National Lab. (United States); Neil T. Zimmerman, Max-Planck-Institut für Astronomie (Germany); Christophe Dorrer, Univ. of Rochester (United States)

Segmented or full aperture telescopes' terrestrial planet finding and characterizing coronagraphic designs often include apodization to mitigate diffraction and aberrations from mirrors' edges, and discontinuities from inter-segment or secondary support structure gaps. When apodizing screens' microdot sizes are comparable to the wavelength of light, surface plasmon effects cause complex chromatic transmission variations. Broadband coronagraphic performance can be severely compromised by such chromaticity. Our far-field transmission measurements of test patches between 0.55–1.1 ?m, using an FTIRS on Brookhaven's National Synchrotron Light Source (NSLS) U10B beamline, revealed ±5% departure from as-designed transmissions. These departures are smaller than those measured on the same test patches between 1.2–2.5 ?m measures on the NSLS' U4IR beamline. We also suggest experimental refinements to improve our calibration accuracy, with the goal of measuring patches as dense as OD3 to better than a percent.

8860-33, Session PMon

Innovative CCD readout technology for use in large focal plane array development

Todd Veach, Paul Scowen, Arizona State Univ. (United States)

Future mission studies will be expecting Hubble-class resolution and extremely wide areal coverage in order to provide the best science return per investment dollar. The only way to combine high resolution imaging with wide areal coverage is to design large FPAs with very small pixel plate scales. The design and construction of a modular imager cell (MIC) using embedded controllers to ameliorate the power, mass, and cost for the large format CCD focal plane arrays, can provide a robust, low-risk, high-reward solution to mitigate possible mission failures by providing a way to assemble large FPAs using a modular "plug and play" solution. By placing the detector and the associated readout electronics on a single module, one can easily remove and replace any single module without adversely affecting other detectors in the FPA. In this paper, I present a prototype design and results for an MIC for use with a delta-doped LBNL 3.5k ? 3.5k CCD. This prototype design is comprised of the CCD preamplification circuitry and CCD control signal filtering circuitry and is scheduled for flight in an upcoming sub-orbital rocket payload.

8860-34, Session PMon

ACCESS: design and subsystem test performance

Mary E. Kaiser, Matthew J. Morris, Stephan R. McCandliss, Johns Hopkins Univ. (United States); Bernard J. Rauscher, Jeffrey W. Kruk, Randy A. Kimble, NASA Goddard Space Flight Ctr. (United States); Edward L. Wright, Univ. of California, Los Angeles (United States); Paul D. Feldman, H. Warren Moos, Russell Pelton, Adam G. Riess, Johns Hopkins Univ. (United States); David B. Mott, Yiting Wen, Dominic J. Benford, Jonathan P. Gardner, NASA Goddard Space Flight Ctr. (United States); Ralph C. Bohlin, Susana E. Deustua, William V. Dixon, David J. Sahnow, Space Telescope Science Institute (United States); Robert Kurucz, Harvard-Smithsonian Ctr. for Astrophysics (United States); Michael Lampton, Saul Perlmutter, Univ. of California, Berkeley (United States)

Improvements in the precision of the astrophysical flux scale are needed to answer fundamental scientific questions ranging from cosmology to stellar physics. ACCESS, Absolute Color Calibration Experiment for Standard Stars, is a series of rocket-borne sub-orbital missions and ground-based experiments that will enable improvements in the precision of the astrophysical flux scale through the transfer of absolute laboratory detector standards from the National Institute of Standards and Technology (NIST) to a network of stellar standards with a

calibration accuracy of 1% and a spectral resolving power of 500 across the 0.35 to 1.7 micron bandpass. The Cassegrain telescope feeds a compact (Rowland circle design) spectrograph with a cross dispersing Fery prism. The detector, a HST/WFC3 heritage 1024x1024 HgCdTe array, is sensitive across the full 0.35 to 1.7 micron bandpass Ground based characterization of the detector, fabrication of the payload and fabrication, integration, and automation of the ground-based calibration subsystem are in progress. The ACCESS design, calibration strategy, and ground-based integration and test results will be presented. Launch is expected within the year. NASA sounding rocket grant NNX08AI65G and DOE DE-FG02-07ER41506 support this work.

8860-35, Session PMon

A design and trial production of the image slicer unit for the mid-infrared spectrograph

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An integral field spectroscopic function plays an extremely important role for next generation infrared instruments in, for example, understanding the dust condensation processes around massive stars with active mass loss, unveiling the complicated structures of circumstellar medium around late-type red giants, and characterizing the properties of proto-planetary disks and envelopes. In particular, an image slicer is highly in demand for an integral field unit (IFU) spectrograph of the next generation infrared telescopes. We have obtained the optical layout of the image slicer for SPICA mid-infrared Camera and Spectrometer (MCS) medium resolution spectrometer (MRS). In this case, the refocused image with a field-of-view size of 6 arcsec by 12 arcsec is divided into 5 slitlets by the slice mirror and, then, the image of each slitlet refocused by the spherical pupil mirror is aligned on the pseudo slit mirror and, finally, a pseudo slit image is obtained. We also have carried out the trial production of the key optical elements including the monolithic small format slice mirror (with 5 slices), the monolithic pupil mirror, and the monolithic pseudo slit mirror. In this presentation, we present the results of the processing precision evaluation for those optical elements.

8860-36, Session PMon

Conceptual design of a NIR imaging spectrometer for the Korean next small satellite 1

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Since end of 2012, Korea Astronomy and Space Science Institute (KASI) has been developed the Near-infrared Imaging Spectrometer for Star formation history (NISS), which is a payload of the Korean next small satellite 1 (NEXTSat-1) and will be launched in 2016. NISS has a cryogenic system, which will be cooled down to around 200K by a radiation cooling in space. NISS is a catadioptric telescope with 200mm aperture and F-number 4.2, which covers the observation wavelengths from 0.95um to 3.8um by using the linear variable filter (LVF) for the near infrared spectroscopy. The field of view is 1.7deg. x 1.7deg. and the pixel scale is around 6 arcsec. Optical elements consist of hyperbolic primary and secondary mirrors and one corrector lens to suppress field curvature. The main requirement for the optical performance is that the RMS spot diameters for whole fields are smaller than the detector pixel, 18um. Two LVFs will be used for 0.9-1.9um and 1.9-3.8um, whose FWHM is less than 2%. We will use the coated aluminum mirrors and employ the H1RG 1024x1024 detector made by Teledyne. This paper presents the conceptual design of NISS.

8860-39, Session PMon

Physical optics effects on PSF: amplitude, phase, polarization

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The point spread function (PSF) for telescopes and instruments is determined by the optical aberrations in the telescope - instrument system. In this paper we will examine in detail the three aberration sources that dominate image quality in optical systems: amplitude, phase and polarization. The primary mirror modifies the polarized light content of the scene. Optical elements and devices further on in the optical system modify this polarization further to affect the quality of radiometry, the shape of the point spread function and the image quality. Interactions occur between amplitude, phase and polarization aberrations to degrade image quality across the FOV of most optical systems used for precision remote sensing.

8860-40, Session PMon

The Geospace Dynamics Observatory: a paradigm-changing Geospace mission

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The Geospace Dynamics Observatory (GDO) mission will observe Geospace with unprecedented resolution, scale and sensitivity. At a distance of 60 Re in a near-polar circular orbit and a 27-day period, GDO will image the earth's full disk with (1) three far ultraviolet imagers, (2) an extreme ultraviolet imager of the plasmasphere, and (3) a spectrometer in the near to far ultraviolet range that will probe any portion of the disk and simultaneously observe the limb.

The exceptional capabilities of the GDO mission include (1) unprecedented improvement in signal to noise for global-scale imaging of Earth's space environment that enable changes in the Earth's space environment to be resolved with orders of magnitude higher in temporal and spatial resolution compared to existing data and other approaches, and (2) unrivaled capability for resolving the temporal evolution, over many days, in local time or latitude with a continuous view of Earth's global-scale evolution while simultaneously capturing the changes at scales smaller than are possible with other methods.

This combination of new capabilities is a proven path to major scientific advances and discoveries. The GDO mission will (1) have the first full disk imagery of the storm and circulation systems of the upper atmosphere, (2) be able to image the ionosphere on a global and long time scale basis (3) be able to probe the mechanisms that control the evolution of planetary atmospheres, and (4) be able to test our understanding of how the Earth is connected to the Sun.

This talk will explore the optical and technical aspects of the GDO mission and the implementation strategy. Additionally, the case will be made that GDO will address a significant position of the priority mission science articulated in the recent Solar and Space Physics Decadal Survey.

8860-41, Session PMon

The LBT experience of adaptive secondary mirror operations for routine seeing- and diffraction-limited science operations

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The Large Binocular Telescope (LBT) is unique in that it is currently the only large telescope (2 x 8.4m primary mirrors) with permanently mounted adaptive secondary mirrors (ASMs). These ASMs have been used for regular observing since early 2010 on the right side and since late 2011 on the left side. They are currently regularly used for seeing-limited observing as well as for selective diffraction-limited observing and are required to be fully operational every observing night. By comparison the other telescopes using ASMs, the MMT and more recently Magellan, using fixed secondaries of seeing-limited observing and switch in the ASMs for diffraction-limited observing. We will discuss the night-to-night operational requirements for ASMs specifically for seeing-limited but also for diffractionlimited observations based on the LBT experience. These will include preparation procedures for observing (mirror flattening and resting as examples); hardware failure statistics and how to deal with them such as for the actuators; observing protocols; and current limitations of use due to the ASM technology such as the minimum elevation limit (25 degrees) and the hysteresis of the gravity-vector induced astigmatism. We will also discuss the impact of ASM maintenance and preparation on science observing time and describe our experience of the systems' performance and calibration reliability.

8861-59, Session PMon

Concept study X-ray testing for NICER's X-ray concentrators

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We performed a series of X-ray tests to measure and assess the current performance of the X-ray concentrators to be used for the Neutron star Interior Composition ExploreR (NICER) during the mission's concept study stage. NICER will use 56 grazing incidence X-ray concentrators (XRCs) as the optical system with each module focusing the incoming photons to co-aligned silicon drift detectors with a 2 mm aperture. Successful X-ray timing and navigation studies require optimal signal to noise. Thus by optimizing high throughput concentrators with a large collecting area we can minimizing the PSF and reduce the aperture size in the detector, reducing background. To analyze the optics' performance we used a 600 meter X-ray beam line to collimate the photons, a soft X-ray source, and an X-ray CCD as the detector. A series of different engineering test units were used to perform these studies by measuring the effective area, producing vignetting functions, analyzing current resolution, and comparing the effects on the module after vibration. We have shown that the concentrators are satisfying the mission's minimum requirements.

8861-60, Session PMon

Improvement of microroughness in slumped glass foils for X-ray telescopes via dip coating

Bianca Salmaso, Andrea Bianco, Oberto Citterio, Giovanni Pareschi, Laura Preserpio, Daniele Spiga, INAF - Osservatorio Astronomico di Brera (Italy)

A dip-coating technique is investigated to improve the surface smoothness and consequently the image quality, of X-ray glass segmented mirrors manufactured by hot slumping. This kind of mirrors is currently developed at INAF Osservatorio Astronomico di Brera using the direct slumping technique, in which the shape of a mandrel is replicated on the optical surface of the mirror being produced. To date, the best results were achieved with a mould in Zerodur K20 and glass foils made of aluminum-borosilicate glass type AF32 by Schott. Nevertheless, several factors in the fabrication process trigger deviations from the desired surface microroughness. In order to reduce the microroughness, a suitable coating has been applied to the replicated glass surface by means of dip-coating technique. In this paper we describe the coating technique, the different implemented processes and the results obtained.

8861-61, Session PMon

Reflective and antireflective coatings for the optical chain of the ASTRI prototype

Giacomo Bonnoli, Rodolfo Canestrari, Giovanni Pareschi, INAF - Osservatorio Astronomico di Brera (Italy)

ASTRI, a flagship project of the Italian Ministry of Research (MIUR), is devoted to the realization, operation and scientific validation of an end- to-end prototype for the Small Size Telescope (SST) envisaged to be-come part of the Cherenkov Telescope Array (CTA). The ASTRI proto-type is a dual mirror Imaging Air Cherenkov Telescope (IACT), following the Schwarzschild-Couder design, and adopts an innovative Silicon Photo Multiplier (SiPM) camera. With its 4m wide primary the telescope will be sensitive to multi-TeV Very High Energy (VHE) gamma rays up to 100 TeV and above, with a point spread function of _ 2 arcminutes and a wide (semiaperture 4.8?) field of view. Fully dielectric multi-layer coatings for the primary mirror have been developed and tested, aiming to filter out the large Night Sky Background contamination at wavelengths _ & 650 nm. A reimaging system based on thin (2.5 mm thick) pyramidal light guides will be installed on the focal plane aiming to minimize dead areas. An anti-reflective coating optimized for a wide range of incident angles faraway from normality was developed to enhance the UV-optical transparency of these elements. The issue, strategy, simulations and experimental results are thoroughly presented.

8861-62, Session PMon

Extreme and near ultraviolet experimental facility for calibration of space instrumentation

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Calibration of optical systems is a fundamental step in the development of a space instrumentation which requires dedicated tools. For these kinds of activities, a new facility devoted to space instruments characterization in the Extreme and Near ultraviolet has been developed and its characterization is presented in this work. A monochromator working in the 40-350 nm wavelength range is coupled with a chamber (a tube of 80 cm diameter, and 2 m length) served by a vacuum system able to reach a pressure of 10-7mbar. Inside, a two axis platform allows the rotation of the instrument with respect to the collimating beam coming from the monochromator, in order to test the response of the instrument to light coming from different points of the field of view. Different sources can be adopted such as spectral lamps or brighter hollow cathode

lamps. The next usage of this facility is foreseen during the ground calibration activities of PHEBUS, the spectrometer that will be onboard of Bepicolombo.

8861-1, Session 1

The ASTRI prototype for the next generation of Cherenkov telescopes: structure and mirrors

Rodolfo Canestrari, INAF - Osservatorio Astronomico di Brera (Italy); Enrico Giro, INAF - Osservatorio Astronomico di Padova (Italy); Giovanni Pareschi, INAF - Osservatorio Astronomico di Brera (Italy)

The next generation of IACT (Imaging Atmospheric Cherenkov Telescope) will explore the uppermost end of the VHE domain up to about few hundreds of TeV with unprecedented sensibility, angular resolution and imaging quality.

To this end, INAF (Italian National Institute of Astrophysics) is currently developing a scientific and technological telescope prototype for the implementation of the CTA (Cherenkov Telescope Array) observatory. ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) foresees the full design, development, installation and calibration of a Small Size 4 meter class Telescope. It has an aplanatic, wide field, double reflection optical layout in a Schwarzschild-Couder configuration.

In this paper we report about the technological solutions adopted for the telescope and for the mirrors. In particular the structural and electro-mechanical design of the telescope, now under fabrication, and the results on the optical performances retrieved from mirror prototypes.

8861-2, Session 1

Status of the technologies for the production of the Cherenkov Telescope Array (CTA) mirrors

Giovanni Pareschi, INAF - Osservatorio Astronomico di Brera (Italy)

The Cherenkov Telescope Array (CTA) is the next generation very high energy gamma-ray observatory, with at least 10 times higher sensitivity than current instruments. CTA will comprise several tens of Imaging Atmospheric Cherenkov Telescopes (IACTs) operated in array-mode and divided into three size classes -- large, medium and small telescopes. The total reflective surface could be up to 10,000 m^2 requiring unprecedented technological efforts. The properties of the reflector directly influence the telescope performance and thus constitute a fundamental ingredient to improve and maintain the sensitivity. The R&D status of lightweight, reliable and cost-effective mirror facets for the CTA telescope reflectors for the different classes of telescopes will be reviewed in this talk.

8861-3, Session 1

Schwarzschild-Couder telescope for the Cherenkov Telescope Array: development of the optical system

Julien Rousselle, Univ. of California, Los Angeles (France); Valerie Connaughton, NASA Marshall Space Flight Ctr. (United States) and The Univ. of Alabama in Huntsville (United States); Manel Errando, Barnard College (United States) and Columbia Univ. (United States); Brian Humensky, Columbia Univ. (United States); Reshmi Mukherjee, Barnard College (United States) and Columbia Univ. (United States); Daniel Nieto Garcia, Columbia Univ. (United States); Akira Okumura, Nagoya Univ. (Japan); Vladimir V. Vassiliev, Univ. of California, Los Angeles (United States)

The CTA (Cherenkov Telescope Array) is the next generation ground-?based experiment for very high-?energy (VHE) gamma-?ray observations. It will integrate several tens of imaging atmospheric Cherenkov telescopes (IACTs) with different apertures into a single astronomical instrument. The US part of the CTA collaboration has proposed and is developing a novel IACT design with a Schwarzschild-?Couder (SC) aplanatic two mirror optical system. In comparison with the traditional single mirror Davies-?Cotton IACT the SC telescope, by design, can accommodate a wide field-?of-?view, with significantly improved imaging resolution. In addition, the reduced plate scale of an SC telescope makes it compatible with highly integrated cameras assembled from silicon photo multipliers. In this submission we report on the status of the development of the SC optical system, which is part of the effort to construct a full-?scale prototype telescope of this type at the Fred Lawrence Whipple Observatory in southern Arizona. This project is funded by the NSF Major Research Instrumentation (MRI) program.

8861-4, Session 1

Efficient light collection from crystal scintillators using a compound parabolic concentrator coupled to an avalanche photodiode

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In support of an improved gamma-ray detector for astrophysics and observations of Terrestrial Gamma-ray Flashes (TGFs), we have designed and tested a new approach for the collection and detection of optical photons from scintillators such as Sodium Iodide and Lanthanum Bromide using a light concentrator coupled to an Avalanche photodiode (APD). The APD has many advantages over traditional photomultiplier tubes such as their low power consumption, their compact size, their durability , and their very high quantum efficiency. The difficulty in using these devices in gamma-ray astronomy has been coupling their relatively small active area to the large scintillators necessary for gamma-ray science. Our solution is to use an acrylic Compound Parabolic Concentrator (CPC) to match the large output area of the scintillation crystal to the smaller photodiode. These non-imaging light concentrators exceed the light concentration of focused optics and are light and inexpensive to produce. We present our results from the analysis and testing of such a system including gains in light collecting efficiency, energy resolution of nuclear decay lines, as well as our design for a new, fast TGF detector.

8861-5, Session 2

Scientific prospects in soft gamma-ray astronomy thanks to the LAUE project

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Today, thanks mainly to INTEGRAL and SWIFT, we have a good first idea of the gamma-ray sky in general and about the types of objects that populate this sky. The next obvious step is to zoom-in, focusing on individual objects with the goal of answering specific astrophysical questions about their emission physics, to discover the classes of sources that make the cosmic gamma-ray diffuse background, to solve astrophysical mysteries like the origin of the positron emission line from the Galactic Center region.

All that requires will a significant step in sensitivity comparable to the one done in X-ray by focusing telescopes, like "Einstein" first, after the sky survey obtained with the UHURU satellite.

With the LAUE project, devoted to build a broad band (80-600 keV) lens telescope, we have done a significant step in this direction. With the expected sensitivity and angular resolution that can reached in its passband, we will discuss the new prospects of soft gamma-ray astronomy thanks to Laue lenses .

8861-6, Session 2

The LAUE project and its main results

Enrico Virgilli, Filippo Frontera, Vincenzo Liccardo, Vineeth Valsan, Vito Carassiti, Stefano Chiozzi, Univ. degli Studi di Ferrara (Italy); Stefano Squerzanti, Istituto Nazionale di Fisica Nucleare (Italy); Michele Parise, Univ. degli Studi di Ferrara (Italy); Federico Evangelisti, Univ. degli Studi di Ferrara (Italy) and Istituto Nazionale di Fisica Nucleare (Italy); Marco Statera, Univ. degli Studi di Ferrara (Italy); Vincenzo Guidi, Valerio Bellucci, Riccardo Camattari, Ilaria Neri, Univ. degli Studi di Ferrara (Italy) and Sensors and Semiconductors Lab. (Italy); Ezio Caroli, Natalia Auricchio, Angelo Basili, Stefano Silvestri, John B. Stephen, INAF - IASF Bologna (Italy); Ferdinando Cassese, Luca Recanatesi, DTM S.r.l. (Italy); Claudio Ferrari, Andrea Zappettini, Elisa Buffagni, Consiglio Nazionale delle Ricerche (Italy); Sergio Mottini, Massimiliano Pecora, Thales Alenia Space (Italy); Barbara Negri, Agenzia Spaziale Italiana (Italy)

Focusing telescopes represents a breakthrough for the detection of hard-X and Gamma-rays for Astrophysics. Laue lens is a good candidate to reach the goal of increasing sensitivity and imaging capability with respect to the current direct-viewing telescopes. We will describe the LAUE project, supported by the Italian Space Agency along with a substantial contribution from the Italian industry, whose aim is to demonstrate the capability to build a focusing optics in the hard X-/soft Gamma rays. To show the lens feasibility, a Laue lens petal prototype with 20 m focal length is being built, as a part of an entire lens, made of petals, capable to focus photons in the 80-600 keV energy band. In addition to a detailed description of the new LARIX facility, in which the lens is being assembled, we will report the main results of the project.

8861-7, Session 2

The ground support equipment for the LAUE project

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Wide band Laue lens imaging is a challenging technology with possible important applications in hard X- and ?-ray space instrumentation in the coming decades. In the framework of a project funded by the Italian Space Agency dedicated to the development of a reliable technology to assemble a wide band Laue lens for use in space, our group had the responsibility for the realization of the ground support equipment (GSE). The GSE was implemented in a hard X-ray beam line built at the University of Ferrara and had the main purpose of controlling the assembly of crystals on the Laue lens petal and to verify its final performance. The GSE incorporates the management and control of all the movements the beam line mechanical subsystems and of the precision positioner (based on an Hexapod tool) of crystals on the petal, as well as the acquisition, storing and analysis of data obtained from the focal plane detectors (a HPGe spectrometer and a X-ray flat panel imager). The GSE is based on two PC's connected through a local network: one, placed inside the beam line, to which all the movement subsystems and the detector I/O interface and on which all the management and acquisition S/W runs, the other in the control room allows the remote control and implements the off-line analysis S/W of the data obtained from the detectors. Herein we report on the GSE structure with its interface with the beam line mechanical system, with the fine crystal positioner and with the focal plane detector. Furthermore we describe the SW developed for the handling of the mechanical moving subsystems and for the analysis of the detector data with the procedure adopted for the correct orientation of the crystals before their bonding on the lens petal support.

8861-8, Session 2

Results versus expectations obtained with the LAUE project

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As part of the LAUE project for focusing hard X-/gamma rays, a petal of the complete lens is being assembled at the LARIX facility in the Department of Physics, University of Ferrara. The lens petal structure is composed of bent Germanium and Gallium Arsenide crystals in transmission geometry. We will present the test results obtained from the developed petal and compare them with the expectations derived from a mathematical model of the lens petal. The extension of the model for the complete LAUE project in the 80 – 600 keV energy range will be discussed as well.

8861-9, Session 2

Bent crystal selection and assembling for the LAUE project

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Diffractive crystals have been employed for focusing photons in the 80 – 300 keV energy range in the framework of the LAUE project. For the first time, bent crystals have been used, taking advantage of their high reflectivity and excellent PSF with respect to the mosaic flat crystals. Simulations have already shown their excellent focusing capability which makes them the best candidates for a Laue lens whose sensitivity is driven by the dimension of the focused spot. Bent Germanium (perfect, 111) and Gallium Arsenide (mosaic, 220) were selected with the proper curvature to approach the spherical lens petal surface, with a 20 m long focal length. We will present, along with the obtained results, the measurement technique by which we are able to estimate the exact curvature of each tile within a few percent of uncertainty and their diffraction efficiency.

8861-10, Session 2

Quasi-mosaicity as a powerful tool to investigate coherent effects

Valerio Bellucci, Vincenzo Guidi, Riccardo Camattari, Ilaria Neri, Univ. degli Studi di Ferrara (Italy)

Quasi-mosaicity is a mechanical property driven by anisotropy in diamond-like structure crystals such as Si and Ge. QM crystals were recently proposed as optical components of a Laue lens for focusing hard X-rays (with energy larger than 70 keV). In contrast to a Laue lens based on conventional crystals (e.g. mosaic crystals), usage of QM crystals allows focusing the incident beam in a spot smaller than the dimension of the diffracting crystal. Focusing of photons in a small spot would allow an unprecedented resolution and sensitivity, together with a wide-passband response. In astrophysics, a Laue lens implementing QM crystals should allow observations of cosmic phenomena producing X-ray emissions with high sensitivity. As another, a Laue lens would be useful for imaging in nuclear medicine, leading to a lower radioactive dose imparted to the patient because of no need for tomography scanning. Quasi-mosaicity was also used for bending Si crystals in order to steer high-energy particles via coherent effects in crystals, viz. planar channeling and volume reflection. Channeled or reflected light particles are also useful as sources of gamma ray beams with intense flux, which can be either monochromatic or polychromatic.

8861-11, Session 2

Fabrication of quasi-mosaic Ge crystals for the LAUE project

Riccardo Camattari, Alessandro Battelli, Valerio Bellucci, Ilaria Neri, Vincenzo Guidi, Filippo Frontera, Univ. degli Studi di Ferrara (Italy)

Crystals having curved diffracting planes (CDP) are very promising for broad-band Laue lens, because they allow concentrating X-rays with high reflectivity. However, an intriguing effect of anisotropy in crystal deformation can be exploited to combine the high reflectivity of the CDP with the capability of focusing the radiation onto a very small focal spot. Primary curvature imparted to a crystal results in a secondary (quasi-mosaic) curvature of a different plane direction due to quasi-mosaic effect. Since the size of the focal spot can be controlled by the primary curvature and the quasi-mosaic curvature drives an increase of efficiency diffraction, quasi-mosaic crystals allow focusing with very high resolution. A series of 150 quasi-mosaic samples has been fabricated within the framework of the Laue project for the realization of a Laue lens prototype. Samples are 10x30x2 mm^3 Ge crystals, the planes being parallel to the largest surface are the (211), while quasi-mosaic CDP are the (111). To obtain the focalization of X-rays, the primary radius of curvature of samples is fixed at 40 m, i.e., twice the focal length, which is 20 m for the Laue project. The curvature has been imparted to the samples thanks to the grooving method, which makes it possible to realize self-standing curved plates. Bent quasi-mosaic Ge crystals were analyzed through ?-ray diffraction of their (111) CDP at ILL and ESRF (Grenoble), showing that quasi-mosaic curvature amplifies the diffraction efficiency by more than one order of magnitude with respect to an equivalent crystal without quasi-mosaic curvature.

8861-12, Session 3

X-ray diffraction efficiency of bent GaAs (220) mosaic crystals for the LAUE project

Claudio Ferrari, Elisa Buffagni, Elisa Bonnini, Andrea Zappettini, Consiglio Nazionale delle Ricerche (Italy)

In a Laue lens made by single crystals oriented to diffract parallel x-rays at the lens focus, the energy and angular resolution is limited by the crystal size and by the crystal mosaicity. The use of single crystals bent according to the lens curvature provides a better focussing also by using extended crystals, with the resolution given essentially by the crystal mosaicity.

With this approach a crystal mosaicity as low as 15-25 arcsecond, well below the mosaicity value of copper crystals, was found suitable for the new design of the Laue lens.

Flat mosaic GaAs crystals have been studied at synchrotron gamma rays energies up to 500 keV and using x-ray laboratory sources. The diffraction efficiency as a function of the energy has been measured in different samples. Results in reasonable agreement the with the assumption of nearly perfect mosaic crystals have been found.

The reflectivity and transmission profiles and the integrated intensity have been measured in bent GaAs and Si crystals prepared by the method of surface damaging by using sand paper of different grain size. The surface grinding induces a local lattice strain which produces a self standing bent crystal.

Bent crystals with radius of curvature lower than a critical value given by the extinction length behave as perfect mosaic crystals. It is found that the surface grinding does not affect the crystal diffraction efficiency, the damage thickness being limited to a few tens microns near the crystal surface.

8861-13, Session 3

Crystal bending by surface damage in Si and mosaic GaAs crystals for the LAUE project

Elisa Buffagni, Elisa Bonnini, Andrea Zappettini, Claudio Ferrari, Francesca Rossi, Consiglio Nazionale delle Ricerche (Italy)

Curved crystals, instead of perfect or mosaic crystals, can be used as optical elements of a Laue lens for hard x- and gamma-ray astronomy. In this work we propose to achieve the bending of the crystals by a controlled surface damaging, which introduces defects in a superficial layer of few tens nanometers in thickness undergoing a highly compressive strain.

Several (001) oriented silicon and gallium arsenide wafer crystals have been treated. The local and mean curvature radii of each sample have been determined by means of high resolution x-ray diffraction measurements in Bragg condition at low energy (8 keV). Silicon samples showed spherical curvatures, whereas GaAs treated samples evidenced an elliptical curvature with major axes corresponding to the <110> crystallographic directions. Curvature radii between 3 and 70 m were easily obtained in wafers of different thicknesses. The anisotropy of the crystal curvature is interpreted as due to the different dislocations glide velocity along the [110] and [1-10] directions.

Samples of different surface orientations, such as (100), (111) and (110) have been characterized, showing a dependence of the sample bending on the crystallographic orientation. The characterization of GaAs samples

performed in Laue geometry at gamma-ray energy of 120 keV confirmed the increase of the diffraction efficiency in the bent crystals.

8861-14, Session 3

LAUE lens development led by UC Berkeley: status and prospects

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Laue lenses uniquely enable the concentration of soft gamma rays from a large collecting area onto a focal plane with a reasonably short focal length. In astronomy, they hold the promise of increasing telescope sensitivities by one to two orders of magnitude. The lenses are particularly well suited for observations of faint nuclear gamma ray lines from point sources, but they can also be optimized for continuum sources such as hard X-ray tails from a variety of compact objects.

We report on the status of the Laue lens development effort lead by UC Berkeley, where a dedicated X-ray beamline and a Laue lens assembly station were built, which allowed the realization of a first lens prototype in June 2012. Based on this achievement, and thanks to a new NASA APRA grant, we are moving forward to enable Laue lenses. Several parallel activities are in progress. Firstly, we are refining the method to glue quickly and accurately crystals on a lens substrate. Secondly, we are conducting a study of high-Z crystals to diffract energies up to 900 keV efficiently. And thirdly, we are exploring new concepts of Si-based lenses (for energies below 500 keV) that could further improve the focusing capabilities, increase the angular resolution, and even possibly enable true imaging lenses.

8861-15, Session 3

Bending and bonding Si single crystals for high performance Laue lenses

Marcelo D. Ackermann, Maximilien Collon, Giuseppe Vacanti, Ramses Guenther, Marco W. Beijersbergen, cosine Research B.V. (Netherlands); Nicolas M. Barrière, Univ. of California, Berkeley (United States); Jeroen Haneveld, Micronit Microfluidics BV (Netherlands)

Cosine has developed the technology to bend and directly bond Si mirror plates in order to produce stiff, lightweight X-ray optics which are used for large area space based X-ray telescopes. This technology, Silicon Pore Optics, also allows us to produce other types of high energy optics. Here we present the latest developments in the design and manufacture of a new generation of soft gamma-ray Laue lenses made using SPO technology.

The bending and bonding of 300 ?m thin Si single crystals allows us to fabricate a single crystal with radially curved crystal planes, which strongly improves the focussing properties of a Laue lens. The size of the focal spot is no longer determined by the size of the individual single crystals, but by the accuracy of the applied curvature, which is as low as a few arcseconds. Furthermore, a wedge is incorporated in each individual Si crystal to ensure that all crystals are confocal in the radial direction. A secondary curvature in the axial direction can be used to improve the reflectivity of each crystal, and increase the reflected energy bandwidth. The expected focussing power of this type of Laue lens crystals is so great that even double reflection gamma-ray imaging systems could be considered.

We present the first crystals which are manufactured in the spring of 2013. These are technology demonstrators designed for 125 keV radiation, 5m focal length and 180mm2 frontal area. The first measurements at synchrotron facilities are expected later this year.

8861-16, Session 4

Calibration of the soft x-ray telescopes (SXT) onboard the ASTRO-H satellite

Yang Soong, NASA Goddard Space Flight Ctr. (United States) and The Ctr. for Research and Exploration in Space Science and Technology (United States); Takashi Okajima, Peter Serlemitsos, NASA Goddard Space Flight Ctr. (United States); Devin J. Hahne, Johns Hopkins Univ. Applied Physics Lab. (United States) and NASA Goddard Space Flight Ctr. (United States)

Two soft x-ray telescopes (SXT) onboard ASTRO-H were integrated from four mirror quadrants. Stray-light baffles, in quadrant configuration, were mounted onto the integrated telescope. Thermal control units were also attached to the perimeter of the integrated telescope. The completed instrument went through a series of optical alignment, thus made the quadrant images confocal and their optical axes in parallel to achieve highest throughput possible. Environmental tests were carried out, and optical quality of the telescopes has been confirmed afterwards. The optical and x-ray calibrations include: angular resolution, effective area in the energy range of ~ 0.4 – 12keV, off-axis response, etc. X-ray image half power diameter is at 1 arc-minute level, and the effective area is ~ 87% of the theoretical. PSF of the X-ray image shows the dominant errors of reflectors' figure and of the reflector alignment. Loss of the effective area is mainly due to positional mismatching of their corresponding reflector pairs in the two reflecting stages. Result of the calibrations and suggestions for future improvement will be presented.

8861-17, Session 4

First result from a ground calibration of the hard x-ray telescope onboard ASTRO-H satellite

Takuya Miyazawa, Hiroyoshi Kato, Tadatsugu Demoto, Yuuji Kuroda, Shunya Takizawa, Fumiya Shimasaki, Keisuke Tamura, Yoshito Haba, Kazunori bish Ishibasi, Hironori Matsumoto, Yuzuru Tawara, Hideyo Kunieda, Naoki Ishida, Nagoya Univ. (Japan); Hideyuki Mori, Yoshitomo Maeda, Manabu Ishida, Japan Aerospace Exploration Agency (Japan); Hisamitsu Awaki, Daichi Kurihara, Ehime Univ. (Japan); Kentaro Uesugi, Yoshio Suzuki, Japan Synchrotron Radiation Research Institute (Japan)

We report a first result from a ground-based X-ray calibration of the ASTRO-H Hard X-ray Telescope (HXT) at a synchrotron radiation facility SPring-8. ASTRO-H, to be launched in 2015, is Japan's sixth X-ray satellite mission following to Suzaku satellite. One of the features of ASTRO-H is a simultaneous observation between 0.3 keV to 600 keV with several instruments. ASTRO-H has two HXTs to cover hard x-rays up to 80 keV. HXT, which is one of the key instruments in ASTRO-H, is the conically approximated Wolter-I grazing incidence optics similar to the Suzaku X-ray telescope. Reflector surfaces are coated with depth-graded Platinum and Carbon multilayer to reflect hard X-rays efficiently. In 2011, the integration of the first flight optics (HXT-1) of HXTs were completed, and we performed a ground calibration of HXT-1 at a synchrotron radiation facility, SPring-8 beamline BL20B2 to build a response function of HXT. We use a raster scan method with a pencil beam at the baseline length of 200m. A point spread function and effective area were measured at 30, 40, 50, 60, 70keV. From a preliminary analysis of the data, an angular resolution of 1.5 - 1.9 arcmin. was obtained at five energy bands in the full telescope. The effective area is 170 cm2 at 30 keV and 82 cm2 at 50 keV, respectively. The as-measured effective area at 30 and 50 keV meet the requirement of the ASTRO-H HXT.

8861-18, Session 4

Status of the eROSITA Observatory: testing and calibrating the x-ray mirror assemblies

Vadim Burwitz, Peter Predehl, Peter Friedrich, Heinrich Braeuninger, Elmar Pfeffermann, Wolfgang Burkert, Maria Fürmetz, Gisela Hartner, Benedikt Menz, Max-Planck-Institut für Extraterrestrische Physik (Germany); Gabriele Grisoni, Giuseppe Valsecchi, Fabio Marioni, Media Lario Technologies (Italy)

The eROSITA X-ray observatory that will be launched on board the Russian Spectrum-RG mission comprises seven X-ray telescopes, each with its own mirror assembly (mirror module + X-ray baffle), electron deflector, filter wheel, and CCD camera with its control electronics. The completed flight mirror modules are undergoing many thorough X-ray tests at the PANTER X-ray test facility after delivery, after being mated with the X-ray baffle, and again after both the vibration and thermal-vacuum tests. A description of the work done with mirror modules/assemblies and the test results obtained will be reported here. We will also report on the environmental tests that have been performed on the eROSITA observatory structure / optical bench.

8861-19, Session 4

Development of mirror modules for the ART-XC instrument aboard the Spectrum-Roentgen-Gamma mission

Mikhail V. Gubarev, Brian Ramsey, Stephen L. O'Dell, Ronald F. Elsner, Kiranmayee Kilaru, NASA Marshall Space Flight Ctr. (United States); Carolyn Atkins, The Univ. of Alabama in Huntsville (United States); Mikhail N. Pavlinskiy, Alexey V. Tkachenko, Igor Y. Lapshov, Space Research Institute (Russian Federation)

The Marshall Space Flight Center (MSFC) is developing x?ray mirror modules for the Astronomical Roengen Telescope- X-ray Concentrator (ART?XC) instrument on board the Spectrum?Roentgen?Gamma Mission. ART?XC will consist of seven co?aligned x?ray mirror modules with seven corresponding CdTe focal plane detectors. Each module provides an effective area of 65 cm2 at 8 keV, response out to 30 keV, and an angular resolution of 45 arcsec or better HPD. We will present a status of the ART x?ray module development at MSFC.

8861-20, Session 5

X-ray optics developments at ESA

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Future high energy astrophysics missions will require high performance novel X-ray optics to explore the Universe beyond the limits of the currently operating Chandra and Newton observatories. Innovative optics technologies are therefore being developed and matured by ESA in collaboration with research institutions and industry, enabling leading-edge future science missions.

Silicon Pore Optics (SPO) and Slumped Glass Optics (SGO) are lightweight high performance X-ray optics technologies being developed in Europe, driven by applications in observatory class high energy astrophysics missions, aiming at angular resolutions of 5" and providing effective areas of one or more square meters at a few keV.

This paper will report on the development activities led by ESA, and the status of the SPO and SGO technologies, including progress on high performance multilayer reflective coatings. In addition, the progress with the X-ray test facilities and associated beamlines will be reported.

8861-21, Session 5

Aberration-free silicon pore x-ray optics

Maximilien Collon, Marcelo D. Ackermann, Ramses Guenther, Giuseppe Vacanti, Marco W. Beijersbergen, cosine Research B.V. (Netherlands); Marcos Bavdaz, Eric Wille, Kotska Wallace, European Space Research and Technology Ctr. (Netherlands); Jeroen Haneveld, Mark Olde Riekerink, Arenda Koelewijn, Micronit Microfluidics B.V. (Netherlands); Coen van Baren, SRON Netherlands Institute for Space Research (Netherlands); Peter Müller, Michael Krumrey, Physikalisch-Technische Bundesanstalt (Germany); Vadim Burwitz, Max-Planck-Institut für Extraterrestrische Physik (Germany)

Silicon Pore Optics is an enabling technology for future L- and M-class astrophysics X-ray missions that require high angular resolution (~5 arc seconds) and large effective area (1 to-2 m? at a few keV). The technology exploits the high-quality of super-polished 300 mm silicon wafers and the associated industrial mass production processes, which are readily available in the semiconductor industry. The plan-parallel wafers have a surface roughness better than 0.1 nm rms and are diced, structured, wedged, coated, bent and stacked to form modular Silicon Pore Optics lenses, which can be grouped into a larger optic. The lenses are assembled from silicon alone, with all the mechanical advantages, and form an intrinsically stiff pore structure.

The optics design was initially based on long (25 to 50 m) focal length X-ray telescopes, which could achieve several arc second angular resolution by curving the silicon mirror in only one direction (conical approximation).

Recently shorter focal length missions (10 to 20 m) have been discussed, for which we started to develop Silicon Pore Optics having a secondary curvature in the mirror that will allow producing Wolter-I type optics, which are on axis aberration-free.

In this paper we will present the new manufacturing process, the results achieved and the lessons learned.

8861-22, Session 5

High resolution and high throughput x-ray optics for future astronomical missions

William W. Zhang, NASA Goddard Space Flight Ctr. (United States)

In this paper we will report on the status of the Next Generation X-ray

Optics work that is going on at NASA Goddard Space Flight Center and NASA Marshall Space Flight Center. This works has two objectives. In the near term, one to three years, we intend to make ready a technology that is capable of matching XMM-Newton's angular resolution (~10") while reducing its mass by an order or magnitude from ~3,000 to ~300 kg/m2. Put it another way, this technology will match Suzaku telescopes mass while improving its angular resolution by more than an order of magnitude from ~120" to ~10". In the long term, three to ten years, we intend to develop a process that is capable of making x-ray telescopes comparable to Chandra in angular resolution while reducing its mass per unit area by a factor of 50, thereby enabling a multi-square-meter collection area on a similar platform. We use slumped glass mirror segments to realize the near term goal, and polished silicon mirrors the long term goal. We are developing a comprehensive process of aligning, bonding, and testing of these extremely lightweight mirror segments and modules.

8861-23, Session 5

Design, construction, and testing of lightweight x-ray mirror modules

Ryan S. McClelland, SGT, Inc. (United States); William W. Zhang, NASA Goddard Space Flight Ctr. (United States); Michael P. Biskach, SGT, Inc. (United States)

The segmented slumped glass X-ray mirror technology being developed at NASA Goddard Space Flight Center (GSFC) has reached sufficient maturity to begin design, construction, and testing of flight-like mirror modules. Launching the mirror modules with integrated thin glass segments while maintaining mirror figure and alignment at ~10 arc-sec angular resolution presents unique design challenges. Issues such as high frequency vibro-acoustic response of the glass mirror segments, strength of the bonds attaching the mirrors to the module structure, and horizontal self-weight deformation of the module are especially challenging. Technology Development Modules (TDMs), holding six mirror segments each, which demonstrate the modules meet generic flight requirements have been designed, constructed, and tested. Successful environmental tests including thermal vacuum, random vibration, acoustic, and shock loading have demonstrated the performance of the TDMs in space flight environments. Results indicate that an X-ray mirror module with ~10 arc-sec angular resolution can be ready for mission implementation in the near future. TDMs holding dozens of mirror segments which will further demonstrate the flight readiness of this technology are currently being designed and analyzed.

8861-24, Session 5

Development of four-stage x-ray telescope (FXT) for DIOS mission

Satoshi Sugita, Yuzuru Tawara, Ikuya Sakurai, Nagoya Univ. (Japan)

FXT (Four Stage X-ray Telescope) has been developed as the best fit optics for DIOS which is a small satellite mission for mapping observation of the warm-hot intergalactic medium.Based on the small diameter demonstration model in last year, we developed a fabrication process of large diameter (over 500 mm) foil mirror.

And then we made a new housing which was full-size of 600 mm diameter and holded mirrors by four stage integrated alignment plates.

In this talk we report a production of the large diameter mirrors and a performance measurement of the new quadrant housing.

8861-25, Session 6

Light-weight glass mirror systems for future x-ray telescopes

Anita Winter, Peter Friedrich, Elias Breunig, Max-Planck-Institut für Extraterrestrische Physik (Germany)

We present our latest results of the glass slumping activities at MPE. We have investigated methods for mounting and integration of the glasses and have further improved our measurement methods. Furthermore we look into new possible materials for future slumping moulds. Three highly polished glass sheets have been slumped on our best slumping mould to date, therefore omitting influence of thickness variations on the slumped glass. These glass segments can be said to represent the best possible glass mirror qualities with the current slumping method at MPE. The results of the X-ray test of these glasses and future outlook are presented.

8861-26, Session 6

Non-touch thermal air-bearing shaping of x-ray telescope optics

Edward Sung, Brandon Chalifoux, Mark L. Schattenburg, Massachusetts Institute of Technology (United States); Ralf Heilmann, MIT Kavli Institute for Astrophysics and Space Research (United States)

Traditional methods for thermal shaping of thin glass x-ray mirrors use a solid mandrel, to which a thin sheet conforms at high temperature. This method results in mid-spatial frequency errors and requires a very slow thermal cycling process lasting on the order of days. This paper reports on progress in the development of a non-contact slumping technique that could solve both drawbacks. As an initial step, we focus on achieving flat surfaces instead of the curvature required for x-ray optics. The thin glass is placed between two precision ground horizontal porous ceramic air bearings and is pushed flat due to air pressure as it is thermally cycled. To keep the glass centered, a closed control loop is used, which consists of custom high temperature fiber optic position sensors and bearing tilt actuation. A previously reported actuation method of using fluid shear force on the surface of the glass via bearing-to-bearing angle has been abandoned in favor of tilting the device to use gravity to control the position of the glass. The thermal cycling time required is ten hours or less. The air bearing technique can produce optical surface shapes quickly and with repeatability, allowing for faster production of high quality x-ray optics.

8861-27, Session 6

Evaluation of the surface strength of glass plates shaped by hot slumping process

Laura Proserpio, Giuseppe Crimi, Bianca Salmaso, Mauro Ghigo, INAF - Osservatorio Astronomico di Brera (Italy); Alberto D'Este, Roberto Dall'Igna, Mirko Silvestri, Stazione Sperimentale del Vetro (Italy); Giancarlo Parodi, Francesco Martelli, BCV Progetti S.r.l. (Italy)

The Hot Slumping Technology is under development by several research groups in the world for the realization of X-ray segmented mirrors: thin glass foils are shaped over a mandrel above their transformation temperature. The performed thermal cycle and related operations might affect the glass strength, both on its surfaces or edges, with possible consequences on the structural design of the whole telescope. No reference technical literature exists since the strength of glass is not an intrinsic property of the material depending only on its composition and fabrication process rather it depends on several parameters, e.g. distribution of surface flaws or residual internal stresses from production

process, connected to any of the manufacturing steps. It is therefore extremely important to test the mechanical strength of the glass after it underwent the slumping process, to obtain reliable data to be employed in the structural analyses. The Astronomical Observatory of Brera (INAF-OAB) conducted a deep analysis at this regards, with the collaboration of Stazione Sperimentale del Vetro (SSV) and BCV Progetti. The entire study have been realized on glass D263 by Schott, currently considered for the realization of next-generation IXO-like X-ray telescopes. More than 200 slumped samples of dimension 100mmx100mm and thickness 0.4mm, both flat and curved, have been produced following the same manufacturing and handling processes effectively envisaged on real segments; they have been tested with double ring tests and the collected empirical data have been treated with Weibull statistics. The paper describes the entire activity and presents the results obtained.

8861-28, Session 6

High-precision shaping of x-ray telescope optics using ion implantation

Brandon Chalifoux, Edward Sung, Massachusetts Institute of Technology (United States); Ralf Heilmann, MIT Kavli Institute for Astrophysics and Space Research (United States); Mark L. Schattenburg, Massachusetts Institute of Technology (United States)

Achieving both high resolution and large collection area in the next generation of x-ray telescopes requires highly accurate shaping of thin mirrors, which is not achievable with current technology. Ion implantation offers a promising method of modifying the shape of mirrors by imparting internal stresses in a substrate, which are a function of the ion species and dose. This technique has the potential for highly deterministic substrate shape correction using a rapid, low cost process. Wafers of silicon and glass (D-263 and BK-7) have been implanted with Si+ ions at 150 keV, and the changes in shape have been measured using a Shack-Hartmann metrology system. We show that a uniform dose over the surface repeatably changes the spherical curvature of the substrates, and we show correction of spherical curvature in wafers. Modeling based on experiments with spherical curvature correction shows that ion implantation could be used to eliminate higher-order shape errors, such as astigmatism and coma, by using a spatially-varying implant dose. We will report on progress in modelling and experimental tests to eliminate higher-order shape errors. In addition, the results of experiments to determine the thermal and temporal stability of implanted substrates will be reported.

8861-29, Session 6

Development of light weight replicated x-ray optics

Suzanne E. Romaine, Ricardo Bruni, Harvard-Smithsonian Ctr. for Astrophysics (United States); Brian Choi, ReliaCoat Technologies, LLC (United States); Paul Gorenstein, Harvard-Smithsonian Ctr. for Astrophysics (United States); Christopher Jensen, ReliaCoat Technologies, LLC (United States); Brian Ramsey, NASA Marshall Space Flight Ctr. (United States); Richard Rosati, Harvard-Smithsonian Ctr. for Astrophysics (United States); Sanjay Sampath, Stony Brook Univ. (United States)

X-ray astronomy grazing incidence telescopes use the principle of nested shells to maximize the collecting area. Some missions, such as XMM-Newton, and the upcoming Spectrum-Röntgen-Gamma mission use an electroformed nickel replication (ENR) process to fabricate the nested shell grazing incidence X-ray telescope mirror shells. We are developing a process to fabricate metal-ceramic replicated optics which will be lighter weight and potentially much stiffer than current ENR mirror shells.

Recent results on fabrication and testing of these optics is presented.

8861-63, Session 6

Very-high-imaging resolution and large-throughput x-ray telescopes based on monolithic thin shells

Oberto Citterio, Marta M. Civitani, Stefano Basso, Paolo Conconi, Mauro Ghigo, Enrico Mattaini, Alberto Moretti, Giovanni Pareschi, INAF - Osservatorio Astronomico di Brera (Italy); Giancarlo Parodi, BCV Progetti S.r.l. (Italy); Gianpiero Tagliaferri, INAF - Osservatorio Astronomico di Brera (Italy)

The implementation of a X-ray mission with high imaging capabilities, similar to those achieved with Chandra (< 1 arcsec Half Energy Width, HEW), but with a much larger throughput is a very attractive perspective, even if challenging. For such a mission the scientific opportunities, in particular for the study of the early Universe, would remain at the state of the art for the next decades. At the beginning of the new millennium the XEUS mission has been proposed, with an effective area of several m2 and an angular resolution better than 2 arcsec HEW. Unfortunately, after the initial study this mission was not implemented, mainly due to the costs and lack of technology readiness. Currently the most advanced proposal for such a kind of mission is the SMART-X project, led by CfA and involving several other US Institutes. This project is based on adjustable segments of thin foil mirrors with piezo-electric actuators, aiming to achieve an effective area > 2 m2 at 1 keV and an angular resolution better than 1 arcsec HEW. Another attractive technology to realize a X-ray telescope with similar characteristics is being developed at NASA/Goddard. In this case the mirrors are based on Si substrates that are super-polished and figured starting from a bulky Si ingot, from which they are properly cut. Here we propose an alternative method based on precise direct grinding, figuring and polishing of thin (a few mm) glass shells with innovative deterministic polishing methods, as e.g. the bonnet polishing. This is followed by a final correction via ion figuring to obtain the desired accuracy in order to achieve the 1 arc sec HEW requirement. For this purpose, a temporary stiffening structure is used to support the shell from the polishing operations up to its integration in the telescope supporting structure. We will present the technological process under development, the results achieved so far and some mission scenarios based on this kind of optics, aiming to achieve an effective area of 1 m2 and an angular resolution of 1 arcsec HEW.

8861-30, Session 7

Coating and bonding thin mirror segments for lightweight x-ray optics

Kai-Wing Chan, NASA Goddard Space Flight Ctr. (United States)

Next generation's lightweight, high resolution, high throughput optics for x-ray astronomy requires integration of very thin mirror segments with extremely large aspect ratio into a lightweight telescope housing without distortion. Thin glass and silicon substrates with aspect ratio as large as 500 – 1000 can now be fabricated with precision. Subsequent implementation requires distortion-free deposition of reflective metallic films and mounting of these mirrors. We will present the result of thin-film coating with magnetron sputtering and atomic layer deposition, the bonding of these segments into their experimental strongbacks, the metrology and qualification of the remaining uncertainties.

8861-31, Session 7

Alignment measurement and permanent mounting of thin lightweight x-ray mirror segments

Michael P. Biskach, Mark Schofield, SGT, Inc. (United States); William W. Zhang, NASA Goddard Space Flight Ctr. (United

States); Kai-Wing Chan, Univ. of Maryland, Baltimore County (United States); Timo Saha, NASA Goddard Space Flight Ctr. (United States); Ryan S. McClelland, James Mazzarella, SGT, Inc. (United States)

Next generation X-ray optics requires precision alignment and permanent mounting of glass mirror segments. Permanent mounting of each segment must meet optical precision, mechanical strength, as well as long term stability requirements of a multiyear mission. Technology Development Modules (TDM's) containing three aligned and permanently mounted glass segment pairs have been constructed and tested by the (Next Generation X-ray Optics) NGXO team at NASA's Goddard Space Flight Center to demonstrate segment alignment and permanent mounting procedures meet initial performance goals as well as survivability requirements. Improvements to the mirror segment alignment and mounting process in the past 12 months are presented along with associated TDM X-ray test results. Objectives for future work are outlined as the near term effort to produce a fully populated module that meets mission requirements continues.

8861-32, Session 7

Shape control of modular x-ray optics during integration and alignment

Elias Breunig, Peter Friedrich, Anita Winter, Max-Planck-Institut für Extraterrestrische Physik (Germany)

MPE is involved in the development of slumped glass mirrors since many years. We use an indirect slumping method wwhich produce a complete parabola-hyperbola segment in a single piece. Recent advances in mirror quality have raised the need for a better understanding and design of the integration and alignment process.The two key issues are the handling of a mirror segment during assembly where gravity distortion is of concern, and the technology to structurally integrate the mirror segments with the mirror module. This integration has to be dimensionally stable and also robust enough to sustain launch loads.

Both steps can introduce significant shape error to the mirror. Since we pursue a design philosophy that ultimately aims for a zero stress assembly, our approach is based on the application of isostatic mounting principles and gravity compliance to minimize distortion effects. We have conducted FEM Analysis and experimental investigations to show that a vertical suspension mount can serve as a good basis for our mirrors. Especially in conjunction with a isostatic interface to the module structure. However, since such an isostatic mount can not fully support the mirror during launch, additional elements ('launch locks') may have to be introduced into the system. We have conducted numerical analsis of the bonding of the mirror segement to the supporting structure to better optimize the detailed design of the interfaces and we are currently working on an experimental quantification / calibration of those results. We are also investigating the possibility of a adhesive free integration which would have the advantage of being faster and less complicated with respect to the special properties of common adhesives like shrinkage and outgasing.

8861-33, Session 7

Direct hot slumping and accurate integration process to manufacture prototypal x-ray optical units made of glass

Marta M. Civitani, Stefano Basso, Mauro Ghigo, Laura Proserpio, Daniele Spiga, Bianca Salmaso, Giovanni Pareschi, Gianpiero Tagliaferri, INAF - Osservatorio Astronomico di Brera (Italy); Marcos Bavdaz, Eric Wille, European Space Research and Technology Ctr. (Netherlands)

X-ray telescopes with large collecting area, like the proposed International X-ray Observatory (IXO) with around 3m^2 @ 1 keV), need to be composed of a large number high quality mirror segments, aiming at achieving a global spatial resolution better than 5 arcsec (HEW). A possible technology to realize the modular elements that will compose the whole optics, named X-ray Optical Units (XOUs), consists in stacking in Wolter-I configuration several layers of thin foils of borosilicate glass, previously formed by hot slumping. The XOUs are subsequently assembled to form complete multi-shell optics with Wolter-I geometry. The achievable global angular resolution of the optic relies on the required surface shape accuracy of slumped foils, on the smoothness of the mirror surfaces and on the correct integration and co-alignment of the mirror segments. Since few years, the Brera Astronomical Observatory (INAF-OAB), with the support by ESA, is leading a study concerning the production of the mirror segments trought the direct hot slumping of thin glass foils. Moreover an innovative assembly concept making use of Wolter-I counter-forms and glass reinforcing ribs is under developement. The ribs connect pairs of consecutive foils in an XOU stack, playing a structural and a functional role. Infact, as the ribs constrain the foil profile to the correct shape during the bonding , they allow the dump of the low-frequency profile errors still present on the foil after slumping. A dedicated semirobotic Integration MAchine (IMA) has been realized and used to build the first integrated prototypes made of several layers of slumped plates. In this paper we will give an overview of the project and a status report of the results achieved, in particular regarding the development of representative breadboards, based on several confocal shells, calibrated at Panter/MPE

8861-34, Session 8

Updated coating design for ATHENA

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The ATHENA mission concept continues to be refined to address important questions in modern astrophysics. Previous studies have established that the requirement for effective area can be achieved using a combination of bi-layer coatings and/or simple graded multilayers. We find that further coating developments can improve on the baseline specifications and present here the updated results on the optimization of coating design for the ATHENA mission. The performances of several material combinations are investigated with the goal of maximizing the telescope effective area within the energy envelope of the mission and simulation of mirror performance is carried out including realistic effects of scatter and coating non-uniformities both on- and off-axis.

8861-35, Session 8

Optimal coating design for x-ray optic in CERN Axion Solar Telescope

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In this paper, a computer model has been developed to optimize a Wolter I X-ray telescope to be installed at the CERN Axion Solar Telescope (CAST). The geometric configuration was calculated to give maximum throughput with only a 1.5 m focal length. Optical coatings for X-ray reflectivity was optimized with respect to detector quantum efficiency (QE) and axion spectrum. Coatings considered were multilayers and single bilayers of W/Si, W/B4C, Pt/C, Pt/B4C, Ni/B4C and Ni/C as well as single layers of Pt, W, Ni and Ir. A comparison between the optimal coating of each material combination is presented.

8861-36, Session 8

Design scheme and fabrication of the supermirror with broad bandwidth and flattop response for hard x-ray telescopes

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We present our design and fabrication scheme of supermirror with broad bandwidth and flat-top response for hard X-ray telescopes. A Platinum-Carbon Non-periodic multilayer of 123 layer pairs with a varying d-space of 2-6nm were designed and successfully fabricated to enhance the reflectivity in the energy band from 11 to 55keV with flat top of 20% at grazing angle of 0.28deg. It is applicable for hard X-ray optics in general. The structure of this mirror was obtained by a conventional design process, i.e. the combination of an initial multilayer structure and a local optimization process. An evaluation process which consists of 3 steps has been used to check the validity of the designed structure for our application. First, the robustness of the grazing angle has been checked to demonstrate the consistent off-axis response of the designed structure. Second, the concept of “equivalent layer number” has been defined to evaluate the efficiency of the optimization process. Third, the fabrication difficulty has been carefully considered in the practical point of view. Then, a fabrication process has been established and the designed structure was deposited on a float glass by our DC magnetron sputtering system. The energy response has been measured by our X-ray beam line. The measurement result suggests a convincible reflectivity profile which is about 20% with little oscillation in the entire target band.

8861-37, Session 8

High reflectivity multilayers for hard x-ray and soft gamma-ray applications

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Advances in x-ray reflective optics, including innovations in designs, manufacturing, and reflecting coatings, have traditionally come from the astrophysics and x-ray light source communities. The success of observatories like Chandra and XMM-Newton and the number of researchers who use synchrotron (and increasingly free electron lasers) has enabled the use of x-ray optics in a broad range of disciplines, including diagnostics for laser-plasma facilities, biomedical research and national security missions. Here, we report on measurements of WC/SiC multilayers at energies ranging from 8 to 400 keV that were performed as part of a research program for nuclear Safeguards. Fitting to the experimental data indicate that a single model, derived from low energy data, can consistently predict performance across the entire energy band. Reflectivity exceeding 50% was achieved at 386 keV. Above 100 keV, we show that is extremely important to include incoherent scattering effects when interpreting data. These effects are not included in the classical wave treatment typically used to calculate multilayer performance and must be calculated using appropriate Monte Carlo particle transport codes. We describe the WC/SiC systems we have developed, the experimental results and discuss the limits of multilayer performance we think achievable for future astrophysics missions. A companion paper in this conference uses these results to derive point-designs for various high-energy astrophysics missions.

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8861-38, Session 8

Hard x-ray/soft gamma ray telescope designs for future astrophysics missions

Desiree Della Monica Ferreira, Finn E. Christensen, Niels Jørgen S. Westergaard, Anders C. Jakobsen, DTU Space (Denmark); Michael J. Pivovaroff, Marie-Anne Descalle, Regina Soufli, Monica Fernandez-Perea, Nicolai Brejnholt, Julia K. Vogel, Lawrence Livermore National Lab. (United States)

We present several strawman designs of hard X-ray/soft Gamma ray focusing telescopes for future astrophysics missions. The designs are based on depth graded multilayer coatings. These have been successfully employed on the NuSTAR mission for energies up to 80 keV. Recent advancement in demonstrating theoretical reflectivity for multilayer material combinations up to 400 keV, including effects of incoherent scatter, has given the experimental base for extending multilayer designs to the soft Gamma ray range (see also companion paper at this conference) . At the same time, the calibration of the in-flight performance of the NuSTAR mission allows for a solid understanding and modeling of all relevant effects influencing the performance, including optical constants, roughness, scatter, non-uniformities and figure error. Those permit a realistic extension of the predictions for designs going to much higher energies. Similarly, both thin slumped glass and silicon pore optics substrates have been developed to a prototype stage which promises imaging resolution in the sub 10 arcsec range. We present designs based on both types of substrates, taking into consideration all the developments listed above.

8861-39, Session 8

Exploring the near absorption-edge optical constants for enhanced and sensitive grazing incident reflectvity

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Generally speaking, reflectiity of EUV and X-ray radiations is very low. Reflectivity gets even lowest for perpendicular incidences. The thin film multilayers came into picture to resove this problem. By now, the EUV multilayers are well known both in academia and companies for applications in EUV lithography, high resolution imaging, solar corona imaging, attpsecond radation manuplaton, etc..

For a well designed multilayers of atleast two different materials, there is a region of wavelength where the refractive index contrast is higher . Those region of spectrum are actually near the absorption edges of either of the constituent elements. Thus, an EUV mulitlayer designed by taking into considaration such greater index contrast near the absorption edge gives better reflectivity and sensitivity to small parameter fluctuations on the surface and buried layers of few nanometer depth.

Theoretical and numerical studies of reflectvity near Si-L edge for multilayers with Si as one of the multilayer materials are performed here. Multilayers of Si/Mo , Ir/Si and Si/ZrSiO4 are numerically studied. The reflectivity is calculated by adopting the recursive Parrate’s method. Two design models are used for multilayers. The statstical mode(two-layer-model) and the Interlayer model(four-layer-mode) are coded in Matlab. Both of them could fit well to the experimentally measured reflectivity by varying structural and optical parameters of the multilayers. However, the interlayer model have additional advantage in that one can study the phases of the interlayer compounds formed at the interfaces and thier thicknesses. This technique gives encouraging sensitivity to the phases of interlayer formation and thicknesses. In otherwords, it could be instrumental in studying the optical and structreral properties of buried interfaces with better sensitivity level. Its analogy to the XANES but in reflectivity not in absorption.

8861-40, Session 9

Development of lightweight blazed transmission gratings and large-area soft x-ray spectrographs

Ralf Heilmann, MIT Kavli Institute for Astrophysics and Space Research (United States); Alexander R. Bruccoleri, Dong Guan, Mark L. Schattenburg, Massachusetts Institute of Technology (United States)

Large area, high resolving power spectroscopy in the soft x-ray band can only be achieved with a state-of-the-art diffraction grating spectrometer. Recently developed critical-angle transmission (CAT) gratings combine the advantages of transmission gratings (low mass, relaxed figure and alignment tolerances) and blazed reflection gratings (high broad band diffraction efficiency, utilization of higher diffraction orders). Several recently developed mission concepts containing CAT grating based spectrometers (AEGIS, AXSIO, SMART-X) promise to deliver unprecedented order-of-magnitude improvements in soft x-ray spectroscopy figures of merit. The CAT grating principle has previously been demonstrated with x rays using small wet-etched samples. The latest gratings are fabricated from silicon-on-insulator wafers using advanced lithography and a never-before demonstrated combination of highly anisotropic dry and wet etching techniques. We designed and built a setup for the measurement of spectral resolving power of an adjustable CAT grating array, and we shall report on the latest progress in the fabrication and x-ray testing of lightweight, large area gratings with a scalable hierarchy of low-obstruction support structures.

8861-41, Session 9

Nanofabrication advances for high efficiency critical-angle transmission gratings

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We report several break-though nanofabrication developments enabling high efficiency and high resolving power spectrometers in the soft x-ray band. The device is the critical-angle transmission (CAT) grating, which combines the low mass and relaxed alignment tolerances of a transmission grating with the high broad-band efficiency and high diffraction orders of a blazed reflection grating. Past work successfully demonstrated the CAT grating concept; however, the open-area fraction was often less than 20 % whilst more than 50% is desired. This presents numerous nanofabrication challenges including a requirement for a free-standing silicon membrane of ultra high-aspect ratio bars at a period of 200 nanometers with minimal cross support blockage. Furthermore, the sidewalls must be smooth to a few nanometers to efficiently reflect soft x-rays. We have developed a complete nanofabrication process for creating free-standing CAT gratings via plasma-etching silicon wafers with a buried layer of SiO_2. This removable buried layer enables combining a record-performance plasma etch for the CAT grating with a millimeter-scale honeycomb structural support to create a free-standing membrane. We have also developed the first reported process for polishing sidewalls of plasma-etched ultra-high aspect ratio nanoscale silicon structures via KOH. This process utilizes the anisotropic etch nature of single crystal silicon in KOH. We developed a novel alignment technique to align the CAT grating bars to the <111> planes of silicon within 0.2 degrees, which enables KOH to etch away sidewall roughness without destroying the structure, since the <111> planes etch approximately 100 times slower than the non-<111> planes.

8861-42, Session 9

Revamping off-plane x-ray gratings

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X-ray reflection gratings have significant flight heritage from suborbital rockets to XMM-Newton. The off-plane mount is a configuration capable of obtaining the high throughput, high spectral resolving power requirements necessary for achieving key science goals in future NASA Explorer missions and Observatories. We detail the current state of off-plane gratings and highlight recent results in performance testing. We discuss the major difficulties involved with spectrometer development and plans on dealing with these issues. Finally, we present our future plans and a roadmap for technology development.

8861-43, Session 9

Pushing the boundaries of x-ray grating spectroscopy in a suborbital rocket

Randall L. McEntaffer, Casey DeRoo, Ted Schultz, The Univ. of Iowa (United States); William W. Zhang, NASA Goddard Space Flight Ctr. (United States); Neil J. Murray, e2v Ctr. for Electronic Imaging at The Open Univ. (United Kingdom); Stephen L. O'Dell, NASA Marshall Space Flight Ctr. (United States); Webster Cash, Univ. of Colorado at Boulder (United States)

Developments in grating spectroscopy are paramount for meeting the soft X-ray science goals of future NASA X-ray Observatories. While developments in the laboratory setting have verified the technical feasibility of using off-plane reflection gratings to reach this goal, flight heritage is a key step in the development process toward large missions. To this end we have developed a design for a suborbital rocket payload employing an Off-Plane X-ray Grating Spectrometer. This spectrometer utilizes slumped glass Wolter-1 optics, an array of gratings, and a CCD camera. We discuss the unique capabilities of this design, the expected performance, the science return, and the perceived impact to future missions.

8861-44, Session 9

Alignment tolerances for off-plane reflection grating spectrometry: theoretical calculations and laboratory techniques

Ryan Allured, Randall L. McEntaffer, The Univ. of Iowa (United States)

Future NASA X-ray Observatories will shed light on a variety of high-energy astrophysical phenomena. Off-plane reflection gratings can be used to provide high throughput and spectral resolution in the 0.3-2.0 keV band, allowing for unprecedented diagnostics of energetic astrophysical processes. A grating spectrometer consists of multiple aligned gratings intersecting the converging beam of a Wolter-I telescope. Each grating will be aligned such that the diffracted spectra overlap at the focal plane. Misalignments will degrade both spectral resolution and effective area. In this paper we present an analytical formulation of alignment tolerances that define grating orientations in all six degrees of freedom. We verify our analytical results with raytrace simulations to fully explore the alignment parameter space. Finally, we report on the status of laboratory techniques to achieve these tolerances for flight-like optics.

8861-45, Session 9

Progress toward a soft X-ray polarimeter

Herman L. Marshall, Norbert S. Schulz, Massachusetts Institute of Technology (United States)

We are developing instrumentation for an telescope design capable of measuring linear X-ray polarization over a broad-band using conventional spectroscopic optics. Multilayer-coated mirrors are key to this approach, being used as Bragg reflectors at the Brewster angle. By laterally grading the multilayer mirrors and matching to the dispersion of a spectrometer, one may take advantage of high multilayer reflectivities and achieve modulation factors over 50% over the entire 0.2-0.8 keV band. We present progress on laboratory work to demonstrate the capabilities of an existing laterally graded multilayer coated mirror pair. We also present plans for a suborbital rocket experiment designed to detect a polarization level of 10% for an active galactic nucleus in the 0.1-1.0 keV band.

8861-46, Session 10

Straylight baffling and environmental qualification of silicon pore optics

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Silicon Pore Optics (SPO) provide a high angular resolution with a low areal density as required for future X-ray telescopes for high energy astrophysics. We present progress in two areas of ESA's SPO development activities. Straylight baffling and environmental qualification.

Residual straylight originating from off-axis sources or the sky background can be blocked by placing suitable baffles in front of the mirror modules. We developed two different mechanical implementations. The first uses longer, tapered mirror plates which improve the straylight rejection without the need of mounting additional parts to the modules or the telescope. The second method is based on placing a sieve plate in front of the optics. We compare both methods in terms of baffling performance using raytracing simulations and present test results of prototype mirror modules.

Any optics for space telescopes needs to be compliant with the harsh conditions of the launch and in-orbit operation. We present new efforts in improving the mechanical and thermal ruggedness of SPO mirror modules and show recent results of qualification level tests, including tests of modules with externally mounted sieve plate baffles.

8861-47, Session 10

Point spread function derivation of grazing-incidence x-ray mirrors from near-field x-ray full imaging

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The optics of a number of future X-ray telescopes will have very long focal lengths (10 - 20 m), and will consist of a number of nested/stacked thin, grazing-incidence mirror. The optical quality characterization of a real mirror can be obtained via profile metrology, and the Point Spread Function of the mirror can be derived via a standard ray-tracing routine. However, in practical cases it can be difficult to access the optical surfaces of densely stacked mirror shells after they have been assembled, using the widespread metrological tools. For this reason, the assessment of the imaging resolution of a system of mirrors is better obtained via a direct, full-illumination test in X-rays. If the focus cannot be reached, an intra-focus test can be performed, and the image can be compared with the ray tracing based on the metrology, if available. However, until today no quantitative information was extracted from a full-illumination, intra-focal exposure. In this work we show that, if the detector is located close enough to the mirror, the intensity variations of the intra-focal, full-illumination image in single reflection can be used to reconstruct the profile of the mirror surface, without scanning the surface and without the need of a wavefront sensor. The Point Spread Function can be subsequently computed by tracing the rays from the reconstructed mirror shape. We show the application of this method to an intra-focal (8 m distance) test performed at PANTER on an optical module prototype made of hot-slumped glass foils with a 20 m focal length, from which we could derive an expected imaging quality of 16 arcsec HEW.

8861-48, Session 10

Opto-mechanical analyses for performance optimization of lightweight grazing-incidence mirrors

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New technology in grazing-incidence mirror fabrication and assembly is necessary to achieve sub-arcsecond optics for large-area x-ray telescopes. In order to define specifications, an understanding of performance sensitivity to design parameters is crucial. MSFC is undertaking a systematic study to specify a mounting approach, mirror substrate, and testing method. Because the lightweight mirrors are typically flimsy, they are susceptible to significant distortion due to mounting and gravitational forces. Material properties of the mirror substrate along with its thickness and dimensions significantly affect the distortions caused by mounting and gravity. A parametric study of these properties and their relationship to mounting and testing schemes will indicate specifications for the design of the next generation of lightweight grazing-incidence mirrors. Initial results will be reported.

8861-49, Session 11

Hartmann testing of x-ray telescopes

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Optical Hartmann testing of x-ray telescopes is a simple test method to retrieve and analyze alignment errors and low order circumferential errors of x-ray telescopes and its components. A narrow slit is scanned along the circumference of the telescope in front of the primary mirror. The centroids of the images are calculated. From the centroid data, alignment errors, radius variation errors, and cone angle variation errors can be calculated. Mean cone angle, mean radial height (average radius), and the focal length of the telescope can also easily be estimated if the centroid data is measured at multiple focal plane locations.

In this paper we present the basic equations that can be used in the analysis process. These equations can be applied to full-circumference or

segmented x-ray telescopes. We use the Optical Surface Analysis Code (OSAC) to model a segmented x-ray telescope and show that the derived equations and accompanying analysis retrieves the alignment errors and low order circumferential errors accurately.

8861-50, Session 11

Alignment of eROSITA mirrors at the PANTER X-ray test facility

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The development and calibration of eROSITA mirror modules is accompanied by continuous measurements at the X-ray Test Facility PANTER.

To obtain comparable measurement results after each new integration robust alignment procedures are needed to place the mirror module on the optical axis.

Here we present the different methods that we use to align eROSITA like mirror modules. One method uses the symmetry of single reflection images, another one is based on a symmetry of intensity distribution, and the last one on the symmetry of the HEW (half energy width).

8861-51, Session 11

In focus measurements of IXO type optics using the new PANTER x-ray test facility extension

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Future large X-ray observatories in space will require mirrors with large effective areas and long focal lengths. European Space Agency ESA programs for developing light weight optics based on modules of silicon pore optics (SPO) and slumped glas optics (SGO) where put in place for the IXO mission (mirror focal length 20 m and radii 0.74 and 1.00 m). In order to test such optics the MPE PANTER X-ray test facility has been upgraded/extended to accomodate in-focus measurements of such optics modules. We will describe the details of the extension to PANTER as well as the first results obtained from measuring such SPO and SGO modules during the comissioning phase.

8861-52, Session 11

X-ray pencil beam characterization of silicon pore optics

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The characterization of large aperture (> 2 meters), long focal length (> 10 meters) X-ray mirrors for X-ray astronomy with synchrotron radiation poses significant problems related to the available space at synchrotron radiation facilities. Intra-focal pencil beam characterization of part of the optics is advantageous if its results can be shown to have predictive capabilities with respect to the full system.

In this paper we present the routine characterization of silicon pore optics at the PTB X-ray Pencil Beam Facility (XPBF), located at the synchrotron radiation facility BESSY II. In particular we show how measurements taken in the standard XPBF configuration (detector at 5 meter from the optics) can effectively be used to predict the optical performance of the optics at their design focal length. We compare data taken on 20-meter focal length SPO unit in the 20-meter XPBF configuration (available only a few weeks every year) with extrapolated 5-meter measurements. The issue of how to deal with the direct beam contribution to the optical performance of the optics is also addressed.

8861-53, Session 11

Characterising x-ray optics with a collimated x-ray beam: the zone plate approach

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An open question in the measurment of X-ray optics for satellite experiments is what the PSF looks like in orbit and the focal length for an infinite source distance.

In order to measure such a PSF (point spread function) a collimated X-ray beam with a diameter of several centimeters to meters is needed.

For this purpose we have started a study of how to collimate the X-rays using a zone plate.

We present the results of our studies with a zone plate of 122 m focal length at Al-K and a diameter of 5 cm.

We present our configuration study to use such a collimator for measuring long focal length segmented optics for future ATHENA-type X-ray missions.

8861-54, Session 12

Silicon optics for wide field x-ray imaging

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Silicon pore optics (SPO) were originally designed to provide very large collecting areas combined with good angular resolution in narrow field X-ray telescopes. We describe modifications and changes to the geometry and manufacture of SPO to facilitate wide field X-ray imaging applications. Modest changes can greatly improve the vignetting function of SPO in the Wolter I geometry. Reconfiguring SPO to the form Kirkpatrick-Baez stacks in the Schmidt geometry cnd provide very large fields of view with high angular resolution and large collecting area.

8861-55, Session 12

Adjustable x-ray optics and Kirkpatrick-Baez telescopes

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The long term goal of the SMART-X program is the development of a segmented Wolter 1 X-ray telescope whose angular resolution and effective area are superior to the Chandra X-Ray Observatory. SMART-X's methodology consists of applying piezoelectric coatings to the rear of a mirror substrate that has been thermally slumped to the approximate figure. The figure is optimized during ground calibration by adjusting the voltages to the piezoelectric backings, with the capability to optimize imaging performance further on-orbit by viewing a suitably bright point-like object. A similar procedure should be very effective with Kirkpatrick-Baez (KB) telescopes. This author believes it can be performed much more rapidly during ground calibration. The complete line image from a single mirror can be isolated by a moveable slit of variable width, and optimized under computer control. The slit then proceeds to the next mirror and adjusts its width as needed. The two sections can be tuned independently and joined subsequently with rather lenient tolerances. Because of theoretical limitations on its angular resolution a KB telescope cannot replace the Wolter 1 as the ultimate goal of SMART-X but we do suggest that shorter term projects with more modest angular resolution goals, such as a dispersive spectroscopy mission, should consider it. Dispersing the spectrum along the 45 degree direction between the two axes minimizes the effect of scattering similar to what is accomplished by using only part of the azimuth of a Wolter mirror.

8861-56, Session 12

Development status of adjustable grazing incidence optics for 0.5 arcsec x-ray imaging

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We describe progress in the development of adjustable grazing incidence X-ray optics for 0.5 arcsec resolution cosmic X-ray imaging. To date, no optics technology is available to blend high resolution imaging like the Chandra X-ray Observatory, with square meter collecting area. Our approach to achieve these goals simultaneously is to directly deposit thin film piezoelectric actuators on the back surface of thin, lightweight Wolter-I or Wolter-Schwarschild mirror segments. The actuators are used to correct mirror figure errors due to fabrication, mounting and alignment, using calibration and a one-time figure adjustment on the ground. If necessary, it will also be possible to correct for residual gravity release and thermal effects on-orbit.

In this paper we discuss our most recent results in operating multiple adjusters, and extending the process from flat test mirrors to cylindrical and conical test mirror segments. A comparison of modeled and measured influence functions is shown. We also present simulation results showing the process is consistent with the achievement of half arcsec imaging.

8861-57, Session 12

Update to an application using magnetic smart materials to modify the shape of a x-ray telescope mirror

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We describe a technique of shape modification that can be applied to thin walled (~ 100-400 micron thickness) electroformed replicated optics or glass optics to improve the near net shape of the mirror as well as the mid-frequency (~ 2-10 mm length scales) ripple. The process involves sputter deposition of a magnetic smart material (MSM) film onto a magnetically hard material (i.e., one that retains a magnetic field, e.g. the material in hard disk drives). Since the previous report, we have made extensive measurements of the deflection versus magnetic field strength and direction. Here we report those results along with detailed finite element analysis modeling.

8861-58, Session 12

A slatted mirror for an x-ray interferometer manufactured in silicon

Richard Willingale, Gillian I. Butcher, Univ. of Leicester (United Kingdom); Marcelo D. Ackermann, Ramses Guenther, Maximilien Collon, cosine Research B.V. (Netherlands)

A slatted mirror is a unique and crucial component in a particular design for an astronomical X-ray interferometer (Willingale SPIE 2004).

The slats must be thin, <300 microns, flat and co-planar to a very high precision. We describe the manufacture and characterisation of a prototype slatted mirror using an modified form of Silicon pore optics technology.

8862-1, Session 1

Scatter studies for the roughness specifications of the primary mirror of visible emission line coronagraph (VELC) on board ADITYA-1

Suresh N. Venkata, B. Raghavendra Prasad, N. Raj Kumar, Jagdev Singh, Indian Institute of Astrophysics (India)

Visible Emission Line Coronagraph (VELC) on board ADITYA-1 is an internally occulted mirror coronagraph to perform simultaneous narrow-band imaging of solar corona in emission lines centered at 5303 Å (Fe XIV) and 6374 Å (Fe X) over a Field Of View (FOV) of 3 Ro (Ro - Solar Radii) and broad band imaging centered at 5800 Å over a FOV of 6 Ro. To achieve the scientific goals of the mission, instrument background have to be kept minimal (<= 5ppm). One of the major contributions of the instrument background is scatter due to the RMS micro-roughness of the Primary Mirror (M1). Hence, a detailed study of scatter through simulations is carried out in order to arrive at the polishing specifications of M1. Defining an appropriate Bidirectional Scatter Distribution Function (BSDF) plays a crucial role in scatter simulations. For current simulations, we used a three parameter Harvey BSDF defined by bo, S and l. Harvey BSDF holds good for optical surfaces with RMS roughness < 10 Å. Also estimation of RMS roughness correction factor due to finite band width of the profilometer is very important while specifying the RMS roughness of M1. From our simulations we estimate that to maintain 5 ppm scatter level over the FOV, RMS micro-roughness of M1 should be <1.5 Å over the spatial periods from 25 microns to ~ 2 mm at 5000 Å. Simulations are carried out using Advanced System Analysis Program (ASAP), developed by Breault Research Organisation (BRO).

8862-2, Session 1

Effect of field of view and wavelength on scatter distribution at prime focus of visible emission line coronagraph (VELC) on board ADITYA-1

Suresh N. Venkata, B. Raghavendra Prasad, N. Raj Kumar, Jagdev Singh, Indian Institute of Astrophysics (India)

Aditya-1 is India's first space mission for solar coronal observations. It carries Visible Emission Line Coronagraph (VELC) which is an internally occulted mirror coronagraph to low earth orbital. VELC performs simultaneous narrow-band imaging of solar corona in emission lines centered at 5303 Å (Fe XIV) and 6374 Å (Fe X) over a Field Of View (FOV) of 3 Ro (Ro - Solar Radii) and broad band imaging centered at 5800 Å over a FOV of 6 Ro. To achieve the scientific goals of the mission, instrument background have to be kept minimal (<= 5ppm). One of the major contributions of the instrument background is scatter due to the RMS micro roughness of the Primary Mirror (M1). In general, in scatter studies rms micro roughness and surface topography are always in limelight and the effect of other parameters are not given that importance. But in case of VELC, where the source is an extended source (angular size ±16arcmin) and the instrument back ground is to be of the order of few ppm. Hence, a detailed study on the effect of FOV and Wavelength on scatter distribution at the prime focus of VELC was carried out through simulations. In this paper we describe in detail about the results obtained from simulations. Simulations are carried out using Advanced System Analysis Program (ASAP), developed by Breault Research Organization (BRO).

8862-3, Session 1

Improved stray light suppression performance for the solar orbiter/METIS inverted external occulter

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The Solar Orbiter/METIS visible and UV coronagraph introduces the concept of occulter inversion in solar coronagraphy. Classical externally occulted coronagraphs usually have a disk in front of the telescope entrance pupil. According to the mission requirements, in order to reduce the amount of power entering the instrument and to limit the instrument dimensions, METIS is equipped with an inverted external occulter (IEO). The IEO consists of a circular aperture on the Solar Orbiter thermal shield that acts as coronagraph entrance pupil. A spherical mirror (M0), located ~800mm behind the IEO, rejects back the disk-light through the IEO itself. A light-tight boom connects the IEO to the M0 through the thermal shield.

In order to achieve high performance in stray light suppression, the IEO design needs optimization. Due to the novelty of the concept we can only use the heritage of past space-borne coronagraph occulters as a starting point to design a dedicated occulter optimization shape.

A 1.5 years long, accurate test campaign has been carried out to evaluate the best optimization configuration for the IEO. Two prototypes were manufactured to take into account the impact of the boom geometry on the stray light suppression performance. Two optimization concepts were compared: the inverted cone (that derives from the conic optimization of classical occulting disks) and the serrated edge, of which several samples were manufactured, with different geometrical parameters, surface roughnesses and coatings. This work summarizes the activity we have been carrying on to define the flight specifications for the METIS occulter.

8862-4, Session 1

Optimization of baffle configuration for stray light reduction

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Reducing the stray light level is one of the issues that astronomical instruments have to face. In particular, the design of baffles requires special attention in order to minimize the light scattered and diffracted by the edges of the baffle's vanes. The choice of the materials and the treatments used to manufacture these edges can significantly increase the performance of stray light suppression. This is particularly critical for instruments in which the science target is close to a much brighter object

e.g. the solar corona around the Sun disk.

In the framework of the phase B for the solar coronagraph METIS (onboard Solar Orbiter, ESA), we designed a dedicated set-up allowing to evaluate how edge geometry is impacted by black coatings and to identify the possible configurations for SOLO/METIS vanes edges.

In this paper, we compare several edge geometries and finishing in a fast and comprehensive approach.

8862-5, Session 2

HEROES: high-energy replicated optics to explore the sun

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Set to fly in the Fall of 2013 from Ft. Sumner, NM, the High Energy Replicated Optics to Explore the Sun (HEROES) mission is a collaborative effort between the NASA Marshall Space Flight Center and the Goddard Space Flight Center to upgrade an existing payload, the High Energy Replicated Optics (HERO) balloon-borne telescope, to make unique scientific measurements of the Sun and astrophysical targets during the same flight. The HEROES science payload consists of 8 mirror modules, housing a total of 109 grazing- incidence optics. These modules are mounted on a carbon-fiber - and Aluminum optical bench 6 m from a matching array of high pressure xenon gas scintillation proportional counters, which serve as the focal-plane detectors. The HERO gondola utilizes a differential GPS system (backed by a magnetometer) for coarse pointing in the azimuth and a shaft angle encoder plus inclinometer provides the coarse elevation. The HEROES payload will incorporate a new solar aspect system to supplement the existing star camera, for fine pointing during both the day and night. The overall payload will be discussed as well as the new solar aspect system. This mission is funded by the NASA HOPE (Hands On Project Experience) Training Opportunity awarded by the NASA Academy of Program/Project and Engineering Leadership, in partnership with NASA's Science Mission Directorate, Office of the Chief Engineer and Office of the Chief Technologist.

8862-6, Session 2

Solar alpha particles damage effects on UV and EUV optical coatings

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Low energy particles from solar wind plasma contribute to the damage of optical materials, with severe effects on space instruments performance. In the present work the degradation of UV and EUV optical coatings under irradiation by solar alpha particles has been experimentally investigated. A dedicated experiment was realized at the Forschungszentrum Dresden-Rossendorf. The estimation of the total irradiated dose was based on the trajectory that will be kept by the Solar Orbiter satellite, and was varied to represent a total He+ exposure of 1 to 4 years mission. The tested samples include novel multilayer structures based on periodic Mo/Si couples with Ir/Si and Ir/Mo capping layers, designed to enhance the peak of reflectivity at 30.4 nm. Moreover, the experiment was performed on different prototype metallic coatings which were deposited at CNR-IFN U.O.S. Padova for application in the UV-VIS spectral range. The reflectance performance of the samples has been compared prior and after the experiment.

The throughputs from the outlined research contributed to the validation of the proposed structures for potential application to the METIS coronagraph on board the Solar Orbiter spacecraft and future solar instruments.

8862-33, Session 2

Test of a multilayer-coated EUV grating for I-IV order spectroscopic measurements of the solar corona

Luca Poletto, Fabio Frassetto, IFN-CNR LUXOR Lab. (Italy); Angelo Giglia, Istituto Officina dei Materiali CNR (Italy); Stefano Nannarone, Univ. degli Studi di Modena e Reggio Emilia (Italy); Paolo Miotti, Maria-Guglielmina Pelizzo, Paola Zuppella, IFN-CNR LUXOR Lab. (Italy); Silvano Fineschi, Ester Antonucci, INAF - Osservatorio Astronomico di Torino (Italy); Giampiero Naletto, Piergiorgio Nicolosi, Univ. degli Studi di Padova (Italy); Marco Romoli, Univ. degli Studi di Firenze (Italy)

METIS, the "Multi Element Telescope for Imaging and Spectroscopy", is a coronagraph selected by the European Space Agency to be part of the payload of the Solar Orbiter mission to be launched in 2017. The original METIS proposal included four optical paths: 1) linearly polarized visible-light (590-650 nm), 2) narrow-band ultraviolet HI Lyman-? (121.6 nm), 3) narrow-band extreme-ultraviolet HeII Lyman-? (30.4 nm), 4) spectrographic observations of HI Lyman-? and He II Lyman-??in corona. The development and test activities of the grating for the spectroscopic path are here described. It is optimized to work at near normal incidence and to diffract the 121.6 nm radiation at the first order and the 30.4 nm at its 4th order, consequently the two spectroscopic channels are overlapped on the focal plane. The grating is spherical with variable-line-spaced rulings, 1800 gr/mm central density. The selection of the spectroscopic channel to be acquired, either the 121.6 nm or the 30.4 nm, is made by a suitable filter wheel. The grating is multilayer-coated, to have high efficiency in both the spectral channels. A test prototype has been characterized at the BEAR beamline at the ELETTRA synchrotron in Trieste (Italy). The grating was initially coated by Au and successively by a Mo-Si multilayer optimized at 30.4 nm. The efficiencies at the diffracted orders up to the 4th (i.e., intervals centered at 121.6, 60.8, 40.5 and 30.4 nm) have been measured before and after the multilayer deposition. The quality of the multilayer deposition has been tested by AFM measurements on the grating surface and by reflectivity measurements performed on a test reference mirror. Comparisons between the experimental data and numerical simulations are also shown.

8862-34, Session 2

Recent developments of ASPIICS: a giant solar coronagraph for the ESA/PROBA-3 formation flying mission

Sébastien Vives, Lab. d'Astrophysique de Marseille (France); Jean-Yves D. Plesseria, Univ. de Liège (Belgium); Patrick Levacher, Lab. d'Astrophysique de Marseille (France); Werner Curdt, Max-Planck-Institut für Sonnensystemforschung (Germany); Christophe Guillon, Lab. d'Astrophysique de Marseille (France)

PROBA-3 is a technology mission of the European Space Agency (ESA), devoted to the in-orbit demonstration of formation flying techniques

and technologies. Presently in phase B, PROBA-3 will implement a coronagraph (called ASPIICS, "Association de Satellites Pour l'Imagerie et l'Interferometrie de la Couronne Solaire") that will both demonstrate and exploit the capabilities and performance of formation flying.

ASPIICS is distributed on two spacecrafts separated by 140m with the external occulting disk hosted by one spacecraft and the telescope (optical camera included) on the other one. ASPIICS will perform high spatial resolution imaging of the solar corona from the coronal base (1.04 solar radii) out to 3 solar radii.

ASPIICS is developed by a large consortium of European Institutes and Industries from Belgium, Czech Republic, France, Germany, Greece, Italy, Luxembourg and Russia. The design studies concern the external occulter mounted on one satellite and the telescope on the other one but also the additional metrology tools that will help checking the formation and ensure that the flight configuration is optimal for observations.

PROBA-3/ASPIICS successfully passed the Preliminary Design Review (PDR) in April 2013 and is currently in the implementation phase C/D. The present paper will provide the current status of PROBA-3/ASPIICS, a description of the instrument and its expected performance.

8862-35, Session 2

Development of multilayer coatings for solar orbiter EUV imaging telescopes

Franck Delmotte, Evgueni Meltchakov, Sébastien de Rossi, Françoise Bridou, Arnaud Jérôme, Raymond F. Mercier, Lab. Charles Fabry (France); Frédéric Auchère, Xueyan Zhang, Bruno Borgo, Institut d'Astrophysique Spatiale (France); Marc Roulliay, Institut des Sciences Moléculaires d'Orsay (France)

Since more than 20 years, Laboratoire Charles Fabry and Institut d'Astrophysique Spatiale are involved in development of the EUV multilayer coating for solar imaging. Previous instruments, such as the SOHO EIT and STEREO EUVI telescopes, employed the Mo/Si multilayer coatings, which offered at that time the best efficiency and stability. We present here recent results of the development of highly efficient EUV multilayers coatings at 17.4 nm and 30.4 nm for the Solar Orbiter mission. New multilayer structures, based on a combination of three materials including aluminum, have been optimized both theoretically and experimentally. We have succeeded to reduce interfacial roughness of Al-based multilayers down to 0.5 nm via optimization of the multilayer design and the deposition process. The EUV peak reflectance of Al/Mo/SiC and Al/Mo/B4C multilayer coatings reaches 56% at 17.4 nm, the highest value reported up to now for this wavelength. For instance, the Mo/Si coating of the STEREO EUVI telescopes reflects only about 40% at the same wavelength. We have also optimized specific bi-periodic structures that possess two reflection bands in the EUV range with high spectral selectivity. The EUV reflectivity and spectral purity of single and dual-band coatings studied with synchrotron radiation will be discussed. Since the stability of reflecting multilayer coating is an important issue for space missions, we have also studied the temporal and thermal stability (including thermal cycling) as well as the resistivity of the coatings to high-energy and highdose proton irradiation. Experimental results confirm that Al/Mo/SiC multilayer coatings are good candidates for the Solar Orbiter EUV imaging telescopes.

8862-7, Session 3

Solar chromosphere flare spectrograph

Debi Prasad Choudhary, California State Univ., Northridge (United States); Vasyl Yurchyshyn, Big Bear Solar Observatory (United States); Sanjay Gosain, National Solar Observatory (United States); Damian Christian, California State Univ., Northridge (United States)

This paper describes the optical design of a two channel echelle spectrograph to observe the optical spectra at the locations of flares and explosive events on the Sun. This Solar Chromosphere Flare Spectrograph (SCFS) will record flare spectra in two channels in the wavelength range of 350-890 nm, which has several chromospheric spectral lines. The SCFS have a multi-fiber based slit capable of observing at 100 locations of the active region magnetic field polarity inversion lines. The field of view of SCFS will be 80 x 80 arc sec with spatial resolution of 8 arc sec. The spectral resolution of 60,000 will be adequate for measuring Doppler velocities of about 5 km/s. The instrument is designed using off-the-shelves optical and mechanical parts with minimum fabrication at an in-house machine shop. The SCFS will be integrated with the full-disk Halpha telescope at the Big Bear Solar Observatory that is operating semi-automatically a round the year except for weather interruptions.

8862-8, Session 3

An off-limb solar adaptive optics system: design and testing

Gregory E. Taylor, New Mexico State Univ. (United States); Thomas R. Rimmele, National Solar Observatory (United States)

Prominences are complex magnetic structures observed near the limb of the sun. Prominences can erupt and cause coronal mass ejections that drive space weather. Long-exposure spectroscopy and spectro-polarimetry at near-infrared wavelengths is one of the preferred tools deployed to measure the physical properties of prominences, including the prominence magnetic field. However, the required long-exposure diffraction limited observations of prominences are lacking since solar adaptive optics systems currently are not able to lock onto the faint, low contrast prominence structure. We are developing a prototype adaptive optics system capable of locking-on to H-alpha off-limb prominence structure. A correlating Shack-Hartmann wavefront sensor approach is used. In contrast to solar AO systems operated on-disk the low photon flux of off-limb structure is one of the main performance limiting factors. In this presentation, I will detail the design and system analysis of the prototype limb AO system.

8862-9, Session 3

The advanced technology solar telescope (ATST) project: a construction update *(Invited Paper)*

Mark Warner, Thomas R. Rimmele, Joseph P. McMullin, National Solar Observatory (United States)

The 4m Advance Technology Solar Telescope (ATST) will be the most powerful solar telescope and the world's leading ground-based resource for studying solar magnetism that controls the solar wind, flares, coronal mass ejections and variability in the Sun's output. The project has entered its construction phase. Major subsystems have been contracted, designs are complete, and fabrication has started. As its highest priority science driver ATST shall provide high resolution and high sensitivity observations of the dynamic solar magnetic fields throughout the solar atmosphere, including the corona at infrared wavelengths. A high order adaptive optics system delivers a corrected beam to the initial set of state-of-the-art, facility class instrumentation located in the Coudé laboratory facility. The initial set of first generation instruments consists of five facility class instruments, including imagers and spectro-polarimeters. Development and construction of a four-meter solar telescope presents many technical challenges, including thermal control of the enclosure, telescope structure and optics and wavefront control. A brief overview of the science goals and observational requirements of the ATST will be given, followed by a summary of the design status of the telescope and its instrumentation, including design status of major subsystems, such as the telescope mount assembly, enclosure, mirror assemblies, and wavefront correction.

8862-10, Session 4

Solar orbiter: exploring the sun-heliosphere connection *(Invited Paper)*

Daniel Mueller, Richard G. Marsden, European Space Agency (Netherlands); Orville C. St. Cyr, NASA Goddard Space Flight Ctr. (United States)

Solar Orbiter, the first mission of ESA's Cosmic Vision 2015-2025 programme, promises to deliver groundbreaking science with previously unavailable observational capabilities provided by a suite of in-situ and remote-sensing instruments in a unique orbit. The mission will address the central question of heliophysics: How does the Sun create and control the heliosphere? The heliosphere represents a uniquely accessible domain of space, where fundamental physical processes common to solar, astrophysical and laboratory plasmas can be studied under conditions impossible to reproduce on Earth and unfeasible to observe from astronomical distances. In this talk, we highlight the scientific goals of Solar Orbiter, address the synergy between this joint ESA/NASA mission and other new space- and ground-based observatories, and present the mission's development status.

8862-11, Session 4

Spice EUV spectrometer for solar orbiter mission *(Invited Paper)*

Andrzej Fludra, Douglas K. Griffin, Martin E. Caldwell, Paul Eccleston, Nick R. Waltham, Rutherford Appleton Lab. (United Kingdom); Anne Philippon, Institut d'Astrophysique Spatiale (France); Udo H. Schühle, Max-Planck-Institut für Sonnensystemforschung (Germany); Manfred Gyo, Physikalisch-Meteorologisches Observatorium Davos (Switzerland); Joseph M. Davila, NASA Goddard Space Flight Ctr. (United States); B. Walls, Donald M. Hassler, Southwest Research Institute (United States); Grant J. Munro, ESR Technology Ltd. (United Kingdom)

SPICE is a high resolution imaging spectrometer operating at extreme ultraviolet wavelengths, 70.4 – 79.0 nm and 97.3 - 104.9 nm. It is a facility instrument on the Solar Orbiter mission. SPICE addresses the key science goals of Solar Orbiter by providing the quantitative knowledge of the physical state and composition of the plasmas in the solar atmosphere, in particular investigating the source regions of outflows and ejection processes which link the solar surface and corona to the heliosphere. By observing the intensities of selected lines and line profiles, SPICE will derive temperature, density, flow and composition information for the plasmas in the temperature range from 10,000 K to 10MK. The instrument optics consists of a single-mirror telescope (off-axis paraboloid operating at near-normal incidence), feeding an imaging spectrometer. The spectrometer is also using just one optical element, a Toroidal Variable Line Space grating, which images the entrance slit from the telescope focal plane onto a pair of detector arrays, with a magnification of approximately x5. Each detector consists of a photocathode coated microchannel plate image intensifier, coupled to active-pixel-sensor (APS). Particular features of the instrument needed due to proximity to the Sun include: use of dichroic coating on the mirror to reject the majority of the solar spectrum, particle-deflector to protect the optics from the solar wind, and use of data compression due to telemetry limitations. The current status of the instrument design will be presented.

8862-12, Session 4

Novel space coronagraphs: flexible optical design for multiwavelength imaging and spectroscopy

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The classical optical design for visible-light, solar coronagraphs is based on the traditional optical scheme by Lyot who introduced the stop blocking the light diffraction off the entrance pupil. In the ultraviolet (UV: 10-100 nm), the sun-to-corona intensity ratio is order of magnitudes lower than that in the visible-light. The resulting diffraction off the entrance pupil is therefore negligible. For this reason, UV solar coronagraphs do not require Lyot-stops, but need to be all-reflective

This presentation outlines a general optical scheme for coronagraphs working in both the visible-light (VL) and UV wavelength ranges combining the use of reflective optics with Lyot stops. This scheme has been successfully applied to a sub-orbital coronagraph. Another version of this novel design for visible-light/EUV coronagraphs uses an inverted-occultation scheme in order to minimize the solar flux entering the instrument. This scheme has been adopted for the coronagraph on board the ESA Solar Orbital mission.

The innovative inverted-occultation concept is flexible enough that it could also accommodate a EUV spectrograph using the same basic optical layout. The presentation also describes the potential capabilities of the inverted-occulter coronagraph as a VL/UV imager and EUV spectrograph for future solar missions.

8862-13, Session 4

The solar and heliospheric imager (SoloHI) instrument for the solar orbiter mission *(Invited Paper)*

Russell A. Howard, Angelos Vourlidas, Clarence M. Korendyke, Simon P. Plunkett, Michael T. Carter, Dennis Wang, Nathan Rich, U.S. Naval Research Lab. (United States); Donald R. McMullin, Space Systems Research Corp. (United States); Sean P. Lynch, U.S. Naval Research Lab. (United States); Gregory E. Clifford, Silver Engineering, Inc. (United States); Dennis G. Socker, U.S. Naval Research Lab. (United States); Arnaud F. R. Thernisien, George Mason Univ. (United States); Damien Chua, Mark G. Linton, U.S. Naval Research Lab. (United States); David Keller, James R. Janesick, John R. Tower, SRI International Sarnoff (United States); Paulett C. Liewer, Marco Velli, Eric M. DeJong, Jet Propulsion Lab. (United States); Zoran Miki?, Predictive Science Inc. (United States); Volker Bothmer, Univ. Göttingen (Germany); Pierre L. P. M. Rochus, Jean-Philippe A. Halain, Univ. de Liège (Belgium); Philippe L. Lamy, Lab. d'Astrophysique de Marseille (France)

The SoloHI instrument for the ESA/NASA Solar Orbiter mission will track density fluctuations in the inner heliosphere, by observing visible sunlight scattered by electrons in the solar wind. Fluctuations are associated

with dynamic events such as coronal mass ejections, but also with the "quiescent" solar wind. SoloHI will provide the crucial link between the low corona observations from the Solar Orbiter instruments and the in-situ measurements on Solar Orbiter and the Solar Probe Plus missions. The instrument is a visible-light telescope, based on the SECCHI/Heliospheric Imager (HI) currently flying on the STEREO mission. In this instrument concept, a series of baffles reduce the scattered light from the solar disk and reflections from the spacecraft to levels below the scene brightness, typically by a factor of 1012. The fluctuations are imposed against a much brighter signal produced by light scattered by dust particles (the zodiacal light/F-corona). Multiple images are obtained over a period of several minutes and are summed on-board to increase the signal-to-noise ratio and to reduce the telemetry load. SoloHI is a single telescope with a 40? field of view beginning at 5? from the Sun center. Through a series of Venus gravity assists, the minimum perihelia for Solar Orbiter will be reduced to about 60 Rsun (0.28 AU), and the inclination of the orbital plane will be increased to a maximum of 35? after the 7 year mission. The CMOS/APS detector is a mosaic of four 2048 x 1920 pixel arrays, each 2-side buttable with 11 µm pixels.

8862-14, Session 5

Seeing the corona with the solar probe plus mission: the wide-field imager for solar probe+ (WISPR)

Angelos Vourlidas, Russell A. Howard, Simon P. Plunkett, Clarence M. Korendyke, Michael T. Carter, U.S. Naval Research Lab. (United States); Arnaud F. R. Thernisien, George Mason Univ. (United States); Damien Chua, Dennis G. Socker, Mark G. Linton, U.S. Naval Research Lab. (United States); Paulett C. Liewer, Jeffrey R. Hall, Jet Propulsion Lab. (United States); Jeff S. Morrill, U.S. Naval Research Lab. (United States); Eric M. DeJong, Jet Propulsion Lab. (United States); Zoran Miki?, Predictive Science Inc. (United States); Pierre L. P. M. Rochus, Univ. de Liège (Belgium); Volker Bothmer, Jens Rodman, Georg-August-Univ. Göttingen (Germany); Philippe L. Lamy, Lab. d'Astrophysique de Marseille (France)

The Solar Probe Plus (SPP) scheduled for launch in 2018, will orbit between the Sun and Venus with diminishing perihelia reaching as close as 7 million km (9.5 solar radii). Besides a suite of in-situ probes for the magnetic field, plasma, and energetic particles, SPP will be equipped with an imager. The Wide-field Imager for the Solar PRobe+ (WISPR), with a 90 deg radial by 55 deg transverse field of view, will image the fine-scale coronal structure of the corona, derive the 3D structure of the large-scale corona, and determine whether a dust-free zone exists near the Sun. Given the tight mass constrains of the mission, WISPR incorporates an efficient design of two wide-field telescopes and their associated focal plane arrays based on novel large-format (4kx4k) APS CMOs detectors into the smallest heliospheric imaging package to date. The flexible control electronics allow WISPR to collect individual images at cadences up to 1 second at perihelion or sum several of them to increase the signal-to-noise during the outbound part of the orbit. The use of two telescopes minimizes the risk of dust damage which may be considerable close to the Sun. The dependency of the Thomson scattering emission of the corona on the imaging geometry dictates that WISPR will be very sensitive to the emission from plasma close to the spacecraft in contrast to the situation for imaging from Earth orbit. WISPR will be the first 'local' imager providing a crucial link between the large scale corona and the in-situ measurements.

8862-15, Session 5

Development and test of an active pixel sensor detector for heliospheric imager on solar orbiter and solar probe plus

Clarence M. Korendyke, Angelos Vourlidas, Simon P. Plunkett, Russell A. Howard, Dennis Wang, U.S. Naval Research Lab. (United States); Cheryl J. Marshall, NASA Goddard Space Flight Ctr. (United States); James R. Janesick, SRI International Sarnoff (United States); Samuel Tun, U.S. Naval Research Lab. (United States); John R. Tower, David Keller, SRI International Sarnoff (United States); Gregory E. Clifford, Silver Engineering, Inc. (United States)

The Naval Research Laboratory is developing next generation CMOS imaging arrays for the Solar Orbiter and Solar Probe Plus missions. The device development is nearly complete with delivery scheduled for summer of 2013. The 4Kx4K mosaic array with 10micron pixels is well suited to the panoramic imaging required for the Solar Orbiter mission. The devices have adjustable gain. In high gain, a read noise of 2-3 electrons with a full well of ~30,000 electrons has been measured. In low gain, a read noise of ~20 electrons with a full well of >200,000 electrons has been measured. The devices are robust (>100krad) and exhibit minimal performance degradation with respect to radiation. The device development program will be presented. The device performance characteristics will be described.

8862-16, Session 5

Technology development for the Solar Probe Plus Faraday cup

Mark D. Freeman, Jay A. Bookbinder, Anthony W. Case, Peter S. Daigneau, Thomas M. Gauron, Justin C. Kasper, Harvard-Smithsonian Ctr. for Astrophysics (United States)

The upcoming Solar Probe Plus (SPP) mission requires novel approaches for in-situ plasma instrument design. SPP's Solar Probe Cup (SPC) instrument will, as part of the Solar Wind Electrons, Alphas, and Protons (SWEAP) instrument suite, operate over an enormous range of temperatures, yet must still accurately measure femto-amp currents, and with modest power requirements.

This paper discusses some of the key technology development aspects of the SPC, a Faraday Cup and one of the few instruments on SPP that is directly exposed to the solar disk, where at closest approach to the sun (9.5 solar radii) the intensity is greater than 500 earth-suns. These challenges range from materials characterization at temperatures in excess of 1000C to thermal modeling of the behavior of the materials and their interactions at these temperatures. We discuss the trades that have resulted in the material selection for the current design of the Faraday Cup. Specific challenges include the material selection and mechanical design of insulators, particularly for the high-voltage (up to 8 kV) grid and coaxial supply line, and thermo-optical techniques to minimize temperatures in the SPC, with the specific intent of demonstrating Technology Readiness Level 6 by the end of 2013.

8862-17, Session 5

Mechanical design of the solar probe cup instrument on solar probe plus

Peter S. Daigneau, David Caldwell, Henry W. Bergner, Anthony W. Case, Justin C. Kasper, Mark D. Freeman, Harvard-Smithsonian Ctr. for Astrophysics (United States)

The Solar Probe Cup (SPC) instrument is a sun-facing Faraday Cup slated for launch aboard the Solar Probe Plus (SPP) spacecraft in 2018.

The SPC is the only SPP plasma instrument which will not be shielded behind the SPP Thermal Protection System (TPS). The 7-year SPP mission will take SPC on 24 solar pass-bys at perihelia ranging from 35 Rs to 9.5 Rs. At 9.5 Rs, SPC's Sun-facing surface temperatures could approach 1500 degrees C. This paper details the derived mechanical and structural requirements on the primary SPC mechanical assemblies including its shield, sensor and strut. The SPC requirements derivation flows from the SPP environment and interface definition as of the mid-Phase B or preliminary design/technology development program. SPC instrument performance compliance to date will be covered along with results of developmental testing.

8862-18, Session 5

The design, development, and implementation of a solar environmental simulator (SES) for the SAO faraday cup on solar probe plus

Peter N. Cheimets, Jay A. Bookbinder, Mark D. Freeman, Richard Gates, Thomas M. Gauron, Giora Guth, Justin C. Kasper, Kenneth McCracken, William A. Podgorski, Harvard-Smithsonian Ctr. for Astrophysics (United States)

This paper describes the implementation of a solar simulator ,the Solar Environment Simulator (SES), that can simulate solar optical and IR flux levels up to those encountered at 9.5 solar radii. The paper outlines the design, and the challenges of realizing the SES. It also describes its initial uses for proving out the design of the Solar Wind Electron, Alphas, and Protons (SWEAP) Faraday cup.

The upcoming Solar Probe Plus (SPP) mission requires that its in-situ plasma instrument (the Faraday Cup) survive and operate over an unprecedented range of temperatures. One of the key risk mitigation activities in the current Phase B has been to develop and implement an environmental simulator that will enable thermal testing of the Faraday Cup under-flight like conditions.

The SES has proven to be a workhorse in the process of helping to predict the in-flight performance of the SWEAP Faraday Cup. With continuously variable power control above lamp ignition threshold, the SES has been used to determine the system response to a wide range of incoming flux, thereby making it possible to correlate detailed thermal models to a high degree of certainty.

The SES consists of a set of re-purposed, and slightly re-designed standard movie projectors. The projectors have proven to be an economical and effective means to safely hold and control the xenon short-arc lamps that are the basis of the SES. This paper outlines the key challenges controlling the extremely high flux levels (>70w/cm^2) necessary to make the SES a useful testing facility.

8862-19, Session 6

Space weather measurements with the RAD instrument on the Mars Science Laboratory *(Invited Paper)*

Donald M. Hassler, Southwest Research Institute (United States); Robert F. Wimmer-Schweingruber, Christian-Albrechts-Univ. zu Kiel (Germany); Cary Zeitlin, MSL RAD Science Team, Southwest Research Institute (United States)

The Radiation Assessment Detector (RAD) is a compact, lightweight energetic particle analyzer currently operating on the surface of Mars as part of the Mars Science Laboratory (MSL) Mission. These are the first measurements of the radiation environment on the surface of another planet.

This presentation will provide an overview of the RAD investigation and present the early measurements of the radiation environment during cruise and on the surface of Mars and discuss the importance of providing broad heliospheric coverage and situational awareness of space weather as we plan to send humans out into deep space and to Mars.

RAD is supported by NASA (HEOMD) under JPL subcontract #1273039 to SwRI, and by DLR in Germany under contract with Christian-Albrechts-Universitat (CAU).

8862-20, Session 6

10 years of degradation trends of the SORCE SIM instrument

Stéphane Béland, Thomas N. Woods, Jerald W. Harder, Univ. of Colorado at Boulder (United States)

The Solar Radiation and Climate Experiment (SORCE) is a NASA-sponsored satellite mission providing measurements of incoming x-ray, ultraviolet, visible, near-infrared, and total solar radiation. SORCE is currently in its 10th year of operation.

The Spectral Irradiance Monitor (SIM) instrument has been providing daily solar spectrum covering the wavelength range from 240 to 2400 nm at a resolution between 0.25-33 nm using a single optical element. SIM was designed to provide an absolute accuracy of < 2% over the wavelength coverage and a goal of long term accuracy of 0.03% per year.

The exposure of the optics, detectors and electronics to the harsh space environment causes changes in their properties. With the very high accuracy goals, it is critical to keep track of these changes as precisely as possible throughout the lifetime of the mission.

We will be reviewing the methods used to track and correct for SIM instrumental degradation of the optics and the detectors since the start of the mission.

We will also discuss lessons learned in the design of long lived solar observing missions and how they were applied to the SIM instrument on the coming Total Solar Irradiance Sensor (TSIS) mission.

8862-21, Session 7

Solar sounding rocket instrument development at NASA MSFC/Univ. of Alabama in Huntsville *(Invited Paper)*

Ken Kobayashi, The Univ. of Alabama in Huntsville (United States); Jonathan W. Cirtain, Amy R. Winebarger, NASA Marshall Space Flight Ctr. (United States); Leon Golub, Kelly E. Korreck, Harvard-Smithsonian Ctr. for Astrophysics (United States); Sergey V. Kuzin, P.N. Lebedev Physical Institute (Russian Federation); Robert W. Walsh, Univ. of Central Lancashire (United Kingdom); Craig E. DeForest, Southwest Research Institute (United States); Bart De Pontieu, Alan M. Title, Lockheed Martin Space Systems Co. (United States); William A. Podgorski, Harvard-Smithsonian Ctr. for Astrophysics (United States); Sabrina L. Savage, NASA Marshall Space Flight Ctr. (United States); Ryouhei Kano, Noriyuki Narukage, Ryoko Narukage, National Astronomical Observatory of Japan (Japan); Javier Trujillo-Bueno, Instituto de Astrofísica de Canarias (Spain)

We present an overview of solar sounding rocket instruments developed jointly by NASA Marshall Space Flight Center and the University of Alabama in Huntsville. The High Resolution Coronal Imager (Hi-C) is an EUV (19.3 nm) imaging telescope which was flown successfully in July 2012, demonstrating an unprecedented spatial resolution of 0.2 arcscond. The Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP) is a Lyman Alpha (121.6 nm) spectropolarimeter developed jointly with the National Astronomical Observatory of Japan and scheduled for launch in 2015. The Marshall Grazing Incidence X-ray Spectrograph is

a soft X-ray (0.5-1.2 keV) stigmatic spectrograph designed to achieve 5 arcsecond spatial resolution along the slit.

8862-22, Session 7

Effect of surface scatter upon the MTF of the solar ultra violet imager (SUVI) telescope *(Invited Paper)*

James E. Harvey, Scott Ellis, Richard N. Pfisterer, Photon Engineering LLC (United States)

The solar UV imager (SUVI) is an extreme ultraviolet instrument that will fly on the Geostationary Operational Environmental Satellite (GOES)-R and-S platforms, as part of NOAA's space weather monitoring fleet. It will provide important information on solar activity and the effects of the Sun on the earth and the near-earth environment. This instrument will image the full solar disc in 6 EUV wavebands between 304.8 Å and 93.9 Å. A generalized Cassegrain telescope configuration is employed where six mirror sectors utilize multilayer coatings optimized for the six wavelengths of interest. An aperture shutter is used to select the appropriate sector for observations at a particular wavelength. A thinned, back-illuminated CCD sensor with 21mm (2.5 arcsec) pixels resides in the telescope focal plane. The modulation transfer function (MTF) is usually considered to be the image quality criterion of choice for applications where fine detail in extended images needs to be specified or evaluated. However, the contractual image quality requirement was specified in terms of fractional ensquared energy for a variety of different wavelengths and square sizes. In this paper we will calculate and present MTF plots (as degraded by diffraction, geometrical aberrations and surface scatter effects) for each of the SUVI wavelengths of interest. At the shortest wavelengths of interest, image degradation from surface scatter effects due to residual optical fabrication errors will dominate the effects of both diffraction and geometrical aberrations.

8862-23, Session 7

Results from the first flight of the focusing optics x-ray solar imager (FOXSI) sounding rocket

Lindsay Glesener, Univ. of California, Berkeley (United States); Steven D. Christe, NASA Goddard Space Flight Ctr. (United States); Shin-nosuke Ishikawa, National Astronomical Observatory of Japan (Japan); Brian Ramsey, NASA Marshall Space Flight Ctr. (United States); Tadayuki Takahashi, Shinya Saito, Japan Aerospace Exploration Agency (Japan) and The Univ. of Tokyo (Japan); Robert P. Lin, Univ. of California, Berkeley (United States); Säm Krucker, Univ. of Applied Sciences Northwestern Switzerland (Switzerland) and Univ. of California, Berkeley (United States)

Understanding electron acceleration in solar flares requires X-ray studies with greater sensitivity and dynamic range than are available with current solar hard X-ray observers (i.e. the RHESSI spacecraft). RHESSI employs an indirect Fourier imaging method that is intrinsically limited in dynamic range and therefore can rarely image faint coronal flare sources in the presence of bright footpoints. With greater sensitivity and dynamic range, electron acceleration sites in the corona could be studied in great detail. Both these capabilities can be advanced by the use of direct focusing optics. The recently flown Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket payload demonstrates the feasibility and usefulness of focusing optics for observation of solar hard X-rays. FOXSI features grazing-incidence replicated nickel optics made by the NASA Marshall Space Flight Center and fine-pitch silicon strip detectors developed by the Astro-H team at JAXA/ISAS. FOXSI flew successfully on November 2, 2012, producing images and spectra of a microflare and performing a search for nonthermal emission (4-15 keV) from nanoflares occurring outside of active regions (in the "quiet" Sun). Nanoflares are a candidate for providing the required energy to heat the solar corona to its high temperature of a few million degrees. A future satellite version of FOXSI, featuring similar optics and detectors, could make detailed observations of hard X-rays from flare-accelerated electrons, identifying and characterizing particle acceleration sites and mapping out paths of energetic electrons as they leave these sites and propagate throughout the solar corona.

8862-24, Session 7

Design progress of the solar UV-VIS-IR telescope (SUVIT) aboard SOLAR-C

Yukio Katsukawa, National Astronomical Observatory of Japan (Japan); Kiyoshi Ichimoto, Kyoto Univ. Hida Observatory (Japan); Yoshinori Suematsu, Hirohisa Hara, Ryouhei Kano, National Astronomical Observatory of Japan (Japan); Toshifumi Shimizu, Keiichi Matsuzaki, Japan Aerospace Exploration Agency (Japan)

We present a design progress of the Solar UV-Vis-IR Telescope (SUVIT) aboard the next Japanese solar mission SOLAR-C. SUVIT has an aperture diameter of ~1.5 m for achieving spectro-polarimetric observations with spatial and temporal resolution exceeding Hinode SOT. We have studied structural and thermal designs of the optical telescope as well as the optical interface between the telescope and the focal plane instruments. The focal plane instruments are installed into two packages, filtergraph and spectrograph packages. The spectro-polarimeter is the instrument dedicated to accurate polarimetry in the three spectrum windows at 525 nm, 854 nm, and 1083 nm for observing magnetic fields at both the photospheric and chromospheric layers. We made optical design of the spectrograph accommodating the classical slit spectrograph and the integral field unit (IFU) for two-dimensional coverage with the spectro-polarimetric observation. We are running feasibility study of IFU using fiber bundles consisting of rectangular cores as well as the IR camera system for high-sensitivity observations of the He I 1083 nm line.

8862-25, Session 7

The soft x-ray photon-counting spectroscopic imager for the sun

Taro Sakao, Noriyuki Narukage, Kyoko Watanabe, Japan Aerospace Exploration Agency (Japan); Shin-nosuke Ishikawa, National Astronomical Observatory of Japan (Japan); Shinsuke Imada, Nagoya Univ. (Japan)

We report development activities as well as science with the soft X-ray photon-counting spectroscopic imager for the solar corona that we conceive as a possible scientific payload for the Japanese Solar-C mission whose projected launch around 2019.

The imager employs a grazing-incidence sector mirror of Wolter-I type with which images of the corona are to be taken in a wide temperature range (1 MK to beyond 10 MK) with the highest-ever angular resolution (0.5"/pixel for a focal length of 4 m) as an X-ray telescope for the Sun. Moreover, by employing a back-thinned CMOS image sensor as the focal-plane device, we attempmt to implement photon-counting capability with which imaging-spectroscopy of the X-ray corona will be performed for the first time, in the energy range from ~0.5 keV up to 10 keV. The imaging-spectroscopic observations will provide totally-new information on mechanism(s) for the generation of hot coronal plasmas (heated beyond a few MK) which may be responsible for the formation of the hot cores of solar active regions, those for magnetic reconnection, and even generation of supra-thermal electrons associated with flares.

An overview of instrument outline and science of the soft X-ray imager will be presented. Also, ongoing development activities in Japan towards soft X-ray photon-counting observations, including sub-arcsecond-resolution grazing-incidence mirror, high-speed X-ray CMOS detector,

and possible considerations on NASA sounding rocket experiment as a verification flight, will be reported and their perspective discussed.

8862-26, Session PMon

Recent advances in electronics and software for the METIS coronagraph aboard solar orbiter

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METIS is a visible and UV externally inversely occulted coronagraph selected to fly aboard the Solar Orbiter space mission. Thanks to its own capabilities and exploiting the peculiar opportunities offered by the SO mission profile, the instrument will address some of the still open issues in understanding the physics driving the observed processes in the corona and characterizing the slow and fast components of the solar wind.

Recently the METIS design went thorough a significant revision involving the overall electronics configuration and software functionalities, comprehensive of descoping of some features but also aiming at the improvement of the instrument reliability. As a result the electronics architecture has been simplified enabling a potential cold-strapped redundancy scheme of some subsystems, while the preliminary SW database was defined as well.

We also identified the scientific processing algorithms implementing the instrument functionalities and the image compression capabilities able to match the selected HW resources providing an optimal compromise between complexity and compression ratio.

This paper will describe the revised electronics and software design developed in order to maximise the overall scientific returns with the updated instrument configuration.

8862-27, Session PMon

Charged particle data from the combined x-ray and dosimeter instrument aboard GPS satellites

Richard C. Schirato, Los Alamos National Lab. (United States)

Abstract to come: waiting on export control approval

8862-28, Session PMon

Imaging and detector systems of the gamma-ray imager/polarimeter for solar flares (GRIPS) instrument

Nicole Duncan, Univ. of California, Berkeley (United States); Albert Y. M. Shih, NASA Goddard Space Flight Ctr. (United States); Gordon J. Hurford, Pascal Saint-Hilaire, Andreas Zoglauer, Hazel M. Bain, Univ. of California, Berkeley (United States); Mark S. Amman, Lawrence Berkeley National Lab. (United States); Steven E. Boggs, Robert P. Lin, Univ. of California, Berkeley (United States)

Hard X-ray and gamma-ray emission during solar flares encode information about electron/ion dynamics and provide a proxy to deduce solar atmospheric parameters. Enhanced imaging, spectroscopy and polarimetry of gamma/HXR flare emissions over 20 keV to >~10MeV is needed to study particle transport; the Gamma-Ray Imager/Polarimeter for Solar Flares (GRIPS) instrument is designed to meet these goals. GRIPS' key technological improvements over the current solar state of the art in HXR/gamma-ray energies (RHESSI) include 3D position-sensitive germanium detectors (3D-GeDs) and a single-grid modulation collimator, the Multi-Pitch Rotating Modulator (MPRM). The 3D-GeDs allow GRIPS to reconstruct Compton-scatter tracks of energy deposition within the crystal, providing enhanced background reduction and polarization measurements. Each of GRIPS' sixteen detectors has 250 electrode strips with dedicated ASIC/FPGA electronics. In GRIPS' energy range, indirect Fourier imaging provides higher resolution than focusing optics or Compton imaging techniques. The MPRM grid-imaging system has a single-grid design which provides 2x the throughput of a bigrid imaging system like RHESSI. Quasi-continuous resolution from 12.5 – 162 arcsecs is achieved by varying the grid pitch between 1 - 13mm. This spatial resolution will be capable of imaging the separate footpoints in a variety of flare sizes. In comparison, RHESSI's minimum 35arcsec resolution at the same energy makes footpoints resolvable in only the largest flares. We discuss GRIPS science goals, the instrument overall and recent developments in GRIPS' imaging and detector systems. GRIPS is scheduled for an engineering flight from Fort Sumner in September 2013, followed by two long-duration balloon flights from Antarctica.

8862-29, Session PMon

Preliminary tolererance analysis of the coronagraphic instrument METIS for the solar orbiter ESA mission

Vania Da Deppo, Consiglio Nazionale delle Ricerche (Italy); Giuseppe Crescenzio, INAF - Osservatorio Astronomico di Torino (Italy); Giampiero Naletto, Univ. degli Studi di Padova (Italy); Silvano Fineschi, Ester Antonucci, INAF - Osservatorio Astronomico di Torino (Italy)

METIS, the Multi Element Telescope for Imaging and Spectroscopy, is the solar coronagraph foreseen for the ESA Solar Orbiter mission. METIS is conceived to image the solar corona from a near-Sun orbit in two different spectral bands: in the HI UV narrow band at 121.6 nm, and in the polarized visible light band (590 – 650 nm).

METIS is an externally occulted coronagraph which adopts an "inverted occulted" configuration. The inverted external occulter (IEO) is a small circular aperture after which a small spherical mirror M0 rejects back the disk-light through the IEO, then an annular mirror collects the signal coming from the corona and redirects it toward the telescope secondary mirror.

This paper presents the error budget analysis for this new-concept coronagraph configuration, which incorporates two different sub-channels: the UV imaging and the polarimetric VIS one. The two sub-channels are sharing the telescope optics, then an interference filter transmits the UV light towards the UV detector, while the VIS light is reflected towards the polarimetric unit.

The tolerance analysis is rather complex, in fact not only the optical performance for the two sub-channels has to be maintained simultaneously, but also the positions of the M0 and the occulters (IEO, internal occulter and Lyot stop), which assure the optimal disk light suppression, have to be taken into account as tolerancing parameters.

To guarantee the scientific requirements are optimally fulfilled for the two sub-channels, the preliminary results of manufacturing, alignment and

stability tolerance analysis for the whole instrument will be described and discussed.

8862-30, Session PMon

Characterization of linear polarizers in the wavelength range 100-150 nm (VUV) for solar physics applications

Gerardo Capobianco, INAF - Osservatorio Astronomico di Torino (Italy); A. Marco Malvezzi, Univ. degli Studi di Pavia (Italy); Silvano Fineschi, INAF - Osservatorio Astronomico di Torino (Italy); Juan I. Larruquert, Consejo Superior de Investigaciones Científicas (Spain); Giuseppe Crescenzio, Giuseppe Massone, INAF - Osservatorio Astronomico di Torino (Italy); José A. Aznárez Candao, José A. Méndez, Luis Rodríguez-De Marcos, Consejo Superior de Investigaciones Científicas (Spain); Angelo Giglia, Sincrotrone Trieste S.C.p.A. (Italy) and Consiglio Nazionale delle Ricerche (Italy); Stefano Nannarone, Sincrotrone Trieste S.C.p.A. (Italy) and Consiglio Nazionale delle Ricerche (Italy) and Univ. degli Studi di Modena e Reggio Emilia (Italy); Fabio Frassetto, Univ. degli Studi di Padova (Italy)

VUV polarimetry has been recognized as one of the most powerful diagnostic tools for remote sensing of the solar corona, with the potential of providing accurate space resolved information on magnetic activity through observation of resonance lines of the most abundant species. In an on-going collaboration between our groups from Spain and Italy, a program to design, build and characterize optical components for the VUV region has been activated. In particular, using the beamline BEAR at the synchrotron facility Elettra in Trieste (Italy) we have characterized some thin film reflecting linear polarizers, designed and optimized for the study of polarimetric properties of the HI Ly-alpha at 121.6 nm. The characterizations are performed in wavelengths (from 100 to 150 nm) at different angles of incidence (40 – 80 deg). Some polarizers have shown excellent performances with a reflectivity $R \approx 34\%$ and a modulation factor exceeding 95%. The calibration of several samples is reported and aging effects on some old samples is discussed. One of the calibrated sample will be used for the evaluation of the performances of a new fast calibration set-up facility for VUV.

8862-31, Session PMon

In-flight calibration and astronomical polarimetry in the V-band with solar orbiter/ METIS instrument

Gerardo Capobianco, Giuseppe Crescenzio, Silvano Fineschi, Giuseppe Massone, Alessandro Bemporad, INAF - Osservatorio Astronomico di Torino (Italy)

METIS (Multi Element Telescope for Imaging and Spectroscopy) is one of the remote sensing instruments on board the ESA- Solar Orbiter mission, who will be launched in 2017. The Visible Light channel of the instrument is composed by an achromatic LC-based polarimeter for the study of the linearly polarized solar K-corona in visible light (bandpass: 580-640nm). The in-flight calibration of the channel requires the use of some well knows linearly polarized stars in the FoV of the instrument. The check and the selection of the stars and the use of other astronomical targets (i.e. planets, comets,…) are here discussed. The possibility of measure the degree of linear polarization of some astronomical objects (i.e. Earth, comets,…) is also object of this paper.

8862-32, Session PMon

The visible light source for METIS stray-light tests: preliminary design

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METIS is the UV/VIS coronagraph of the ESA mission Solar Orbiter. One of the main technical drivers of the instrument is the detailed stray-light control, as close to the disk edge the VIS coronal emission is six to about seven order of magnitudes lower than the disk one. The instrument testing procedure must then include a measurement of its stray-light rejection capability, which is a fundamental step in the whole instrument calibration / acceptance process. A preliminary optical design of the optical light source for stray-light test is presented. The main requirements are discussed and two possible solutions are outlined.

8863-2, Session 1

Raytheon low temperature RSP2 cryocooler flight program

Brian R. Schaefer, Raytheon Space & Airborne Systems (United States)

The Low-Temperature Raytheon Stirling / Pulse Tube 2-stage ("LT-RSP2") hybrid cryocooler is a long-life, robust machine designed to operate efficiently at a first stage temperature of 55K and a capacity of 5W and a second stage temperature of 10 K and a capacity of 250mW. While some aspects of the expander warm-end mechanical design are carryovers from the existing High Capacity RSP2, the compressor module and expander cold head have been substantially optimized for increased efficiency and capacity at low cryogenic temperatures. The LT-RSP2 design was finalized in mid-2009, with piece-part fabrication taking place in late 2009 and early 2010. Assembly and initial testing in an ambient benchtop configuration occurred in 2010/2011. The flight program was executed in 2011 and 2012. Major aspects of the mechanical and thermodynamic design will be presented in this paper, including information regarding the final operating point, performance, and packaging details. Results from the fabrication, assembly, and testing will be discussed, as will observations regarding the achieved system performance. Future testing and design enhancement plans will be discussed as well.

8863-3, Session 1

Advanced regenerator testing in the Raytheon dual-use cryocooler

Brian R. Schaefer, Raytheon Space & Airborne Systems (United States)

Significant progress has been made on the Raytheon low cost space cryocooler called the Dual Use Cryocooler (DUC), most notably; the DUC has been integrated and tested with an advanced regenerator. The advanced regenerator is a drop in replacement for stainless steel screens and has shown significant thermodynamic performance improvements. This paper will compare the performance of two different regenerators and explain the benefits of the advanced regenerator.

8863-4, Session 1

Raytheon's next generation compact in-line cryocooler architecture

Brian R. Schaefer, Raytheon Space & Airborne Systems (United States)

Since the 1970s, Raytheon has developed, built, tested and integrated high performance space cryocoolers. Our versatile designs for single- and multi-stage cryocoolers provide reliable operation for temperatures from 10 to 200 Kelvin with power levels ranging from 50 W to nearly 600 W. These advanced cryocoolers incorporate clearance seals, flexure suspensions, hermetic housings and dynamic balancing to provide long service life and reliable operation in ground, air and space environments.

Today, sensors face a multitude of cryocooler integration challenges such as exported disturbance, efficiency, scalability, maturity, and cost. As a result, cryocooler selection is application dependent, oftentimes requiring extensive trade studies to determine the most suitable architecture. To optimally meet the needs of next generation passive IR sensors, the Compact Inline Raytheon Stirling 1-Stage (CI-RS1), Compact Inline Raytheon Single Stage Pulse Tube (CI-RP1) and Compact Inline Raytheon Hybrid Stirling/Pulse Tube 2-Stage (CI-RSP2) cryocoolers are being developed to satisfy this suite of requirements. This lightweight, compact, efficient, low vibration cryocooler combines proven 1-stage (RS1 or RP1) and 2-stage (RSP2) cold-head architectures with an inventive set of warm-end mechanisms into a single cooler module, allowing the moving mechanisms for the compressor and the Stirling displacer to be consolidated onto a common axis and in a common working volume. The CI cryocooler is a significant departure from the current Stirling cryocoolers in which the compressor mechanisms are remote from the Stirling displacer mechanism.

Placing all of the mechanisms in a single volume and on a single axis provides benefits in terms of package size (30% reduction), mass (30% reduction), thermodynamic efficiency (>20% improvement) and exported vibration performance (≤25 mN peak in all three orthogonal axes at frequencies from 1 to 500 Hz). The main benefit of axial symmetry is that proven balancing techniques and hardware can be utilized to null all motion along the common axis. Low vibration translates to better sensor performance resulting in simpler, more direct mechanical mounting configurations, eliminating the need for convoluted, expensive, massive, long lead damping hardware.

8863-5, Session 1

Cryomechanism: a cryogenic rotating actuator

Jean-Christophe Barriere, Michel Berthe, Michael Carty, Jean Fontignie, Didier Leboeuf, Jérome Martignac, Christophe Cara, Patrice Charon, Gilles A. Durand, Damien Bachet, Commissariat à l'Énergie Atomique (France); Bruno Duboué, CEA (France)

Fifteen years ago, CEA started the development of cryogenic rotating actuators for VISIR, an astronomy IR camera mounted on the Very Large Telescope. At Visir first light in 2004, 10 cryogenic rotating actuators, also known as "cryomechanisms", were integrated in the instrument. As VISIR is still operating, cryomechnisms are operated several times a day, without any reported failure.

The cryomechanism has been designed to operate from room temperature to cryogenic environment (down to 4 Kelvin) with the same level of performances. Based on a stepper motor and a gear clutch system, the cryomechanism enables any discrete position to be reached(360 positions a turn for VISIR model) with a very good repeatability: below 100µrad peak to peak. Due to the clutch mechanism, there is no power consumption once the actuation has stopped.

After the VISIR project, CEA undertook the task of performing space qualification tests with the aim of making the cryomechanism compatible with space missions. Relying on test results, a smaller model of the mechanism (200 positions a turn) has been built and cryo-tested.

Today, cryomechanisms are selected for the EUCLID space project. Qualification program will run throughout 2014.

The proposed paper will first describe the baseline requirements, the design and operation principles. Then, the qualification plan will be shown as well as the environment test results with respect to vibrations, thermal cycling and life testing campaigns carried out on a Qualification Model. The synthesis of cryomechanisms capabilities will be presented and design improvements for the EUCLID project will be addressed in the last part.

8863-6, Session 1

Cryogenic optical position encoders for mechanisms in the JWST optical telescope element simulator (OSIM)

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The James Webb Space Telescope (JWST) Optical Telescope Element Simulator (OSIM) is a massive, configurable, cryogenic, optical stimulus for JWST's flight instrument complement – called the Integrated Science Instrument Module (ISIM) – and allows high fidelity ground characterization and calibration of the instruments. Using a collection of remotely operated point sources, a single spherical primary mirror, and several ultra-precise, cryogenic mechanisms, OSIM projects images of those sources to ISIM as if they were stars in the sky according to the same optical prescription as the flight telescope would. A large, X-Y-Z-tip-tilt mechanism known as the Beam Image Analyzer (BIA) carries a point-diffraction interferometer, phase retrieval camera, and radiometer assembly – tools that allow OSIM to be configured to establish the correct optical prescription for each field point and chief ray angle. The BIA surveys the telescope's focal surface, calibrating OSIM for all required ground observations with ISIM. OSIM itself contains two X-Y-Z stages (the Source Plate Mechanism and Pupil Translation Mechanism), two rotary pupil selection wheels (Pupil Select Mechanism), and a two-axis gimbal (for Fold Mirror 3). Each mechanism in OSIM and the BIA navigate according to redundant, cryogenic, absolute, optical encoders – 32 in all operating at temperatures at or below 100 K. This paper discusses OSIM's optical encoder subsystem, the engineering challenges that were met in its development, and the sub-micron and sub-arcsecond performance of OSIM's absolute linear (and Cartesian) and angular encoders, respectively.

8863-7, Session 2

Temperature-dependent refractive index of Cleartran® ZnS to cryogenic temperatures

Douglas B. Leviton, Bradley J. Frey, NASA Goddard Space Flight Ctr. (United States)

In order to enable high quality lens designs using Cleartran® ZnS at cryogenic temperatures, we have measured the absolute refractive index of a Cleartran® ZnS prism as a function of both wavelength and temperature using the Cryogenic, High-Accuracy Refraction Measuring System (CHARMS) at NASA's Goddard Space Flight Center. Cleartran® ZnS is a water clear form of CVD ZnS, and while we have not measured "regular" ZnS, literature values indicate that its refractive index does differ from that of Cleartran® ZnS by 0.001-0.002 depending on wavelength at room temperature. For our Cleartran® measurements, we report absolute refractive index and thermo-optic coefficient (dn/dT) at temperatures ranging from 25 to 300 K at wavelengths from 0.50 to 5.6 microns. We compare our measurements with others in the literature and provide temperature-dependent Sellmeier coefficients based on our data to allow accurate interpolation of index to other wavelengths and temperatures. We generally find good agreement at room temperature between our measured values and those provided by the material's manufacturer.

8863-8, Session 2

Temperature-dependent refractive index measurements of S-FPL51, S-FTM16, and S-TIM28 to cryogenic temperatures

Douglas B. Leviton, Bradley J. Frey, Ross M. Henry, NASA Goddard Space Flight Ctr. (United States)

Using the Cryogenic High Accuracy Refraction Measuring System (CHARMS) at NASA's Goddard Space Flight Center, we measured absolute refractive indices at temperatures from 30 to 300 K at wavelengths from 0.50 to 2.6 microns for three infrared materials in support of lens designs for instruments for two of the world's largest astronomical observatories – the present W.M. Keck Observatory and the future Giant Magellan Telescope (GMT). MOSFIRE – a near-infrared multi-object spectrograph and wide-field camera for the Cassegrain focus of Keck 1 – achieves diffraction limited performance at 120 K owing in part to the accuracy of our measurements of S-FPL51 and S-FTM16 prisms provided by University of California Observatories/Lick Observatory. MOSFIRE's lens design was also based in part on previously published CHARMS measurements of its four other infrared lens materials – ZnSe, CaF2, BaF2, and Infrasil 301. NIRMOS – a near infrared multiple object imager/spectrograph proposed for the GMT – uses S-TIM28 in addition to CaF2 and Infrasil in its multi-element imaging lens design. One S-TIM28 prism fabricated for a previous measurement study was provided by the Harvard College Observatory. We report absolute refractive index and thermo-optic coefficient (dn/dT) for these materials and compare our measurements with others in the literature. We provide temperature-dependent Sellmeier coefficients based on our data to allow accurate interpolation of index to other wavelengths and temperatures. Our uncertainty in absolute index for all samples in this study is limited to about 3 x 10-5 for all wavelengths and temperatures measured.

8863-9, Session 2

Cryogenic refractive index and coefficient of thermal expansion of S-TiH1 glass

Manuel A. Quijada, NASA Goddard Space Flight Ctr. (United States)

The top level science requirements for the Wide Field Infrared Survey Telescope (WFIRST) mission are: • Complete the statistical census of Galactic planetary systems using microlensing; • Determine the nature of the dark energy that is driving the current accelerating expansion of the universe; • Produce a deep map survey of the sky at NIR wavelengths, enabling new and fundamental discoveries ranging from mapping the Galactic plane to probing the reionization epoch by finding bright quasars at z>10. A refractive optical system design has been proposed to accomplish the galaxy redshift survey (GRS) on the WFIRST mission. S-TIH1 type glass is a current candidate for the refractive elements. This instrument is expected to operate in a space environment at temperatures as low as 150K. This paper reports on cryogenic optical property studies performed on S-TIH1 glass samples in order to enable progress toward an optical design that will be valid at the 150K operating temperature. Tests results to be reported include coefficient of thermal expansion (CTE) and cryogenic refractive index data obtained with the Cryogenic High Accuracy Refraction Measuring System (CHARMS) facility at the Goddard Space Flight Center.

8863-11, Session 3

Consequences of cathodoluminescence for cryogenic applications of SiO2-based space observatory optics and coating

Amberly Evans, J.R. Dennison, Gregory Wilson, Justin Dekany, Utah State Univ. (United States); Charles W. Bowers, Robert Meloy, NASA Goddard Space Flight Ctr. (United States); James

B. Heaney, SGT, Inc. (United States)

Disordered thin-film fused silica samples undergoing electron-beam bombardment exhibit cathodoluminescence, showing increased intensity and red-shift at lower temperatures. Such light emission from SiO2/SiOx optical elements or coatings can produce deleterious stray background light in cryogenic space-based astronomical observatories exposed to high-energy electron fluxes from space plasmas. Measurements of radiance of cathodoluminescence on irradiation time, incident flux and energy, sample thickness, and temperature are presented along with a simple disordered band theory model. Calculations are presented of absolute spectral radiances for flux profiles over incident electron energies typical of space environments; these allow prediction of luminescence for specific space applications.

8863-12, Session 3

Diverse electron-induced optical emissions from space observatory materials at low temperatures

J.R. Dennison, Amberly Evans, Justin Dekany, Gregory Wilson, Utah State Univ. (United States); Charles W. Bowers, Robert Meloy, NASA Goddard Space Flight Ctr. (United States)

No Abstract Available

8863-13, Session 3

TBA

No Abstract Available

8863-14, Session 4

The development and analysis of cryogenic optical systems for the rapid infrared imager/spectrometer

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The observational cosmology lab at NASA's Goddard Space Flight Center (GSFC), in collaboration with the University of Maryland, is building the Rapid Infrared Imager/Spectrometer (RIMAS) for the new 4.3 meter Discovery Channel Telescope (DCT). The instrument is designed to observe gamma-ray burst (GRB) afterglows following their initial detection by the Swift satellite. RIMAS will operate in the near infrared (0.9 – 2.4 microns) with all of its optics cooled to ~60 K. The primary optical design includes a collimator lens assembly, a dichroic dividing the wavelength coverage into the "YJ band" and "HK band" optical arms, and camera lens assemblies for each arm. Additionally, filters and dispersive elements are attached to wheels positioned prior to each arm's camera, allowing the instrument to quickly change from its imaging modes to spectroscopic modes. Optics have also been designed to image the sky surrounding spectroscopic slits to help observers pass light from target sources through these slits. Because the optical systems are entirely cryogenic, it was necessary to model the effects of thermal contraction. One result of this work is a lens mount design that keeps lenses centered on the optical axis as the system is cooled. Efforts to design, tolerance and assemble these cryogenic optical systems are presented.

8863-15, Session 4

NIRCam filter wheel assembly design

Béla I. Privári, Lockheed Martin Space Systems Co. (United States)

The Filter Wheel Assembly (FWA) is an integral and important sub-system of the Near Infra-Red Camera (NIRCam) instrument on the James Webb Space Telescope. The FWA mechanism provides the capability to position one of twelve different filters in the optical path of the camera, and also positions one of twelve different pupil optics in the same path. The FWA is therefore comprised of two separate wheel assemblies that can be positioned independently to provide the desired configuration of optical elements for imaging. Along with the rest of the instrument, the FWA operates at cryogenic temperatures and is used for both short and long wavelength imaging . Also contained within the FWA is a calibration light source assembly used for confirming detector performance throughout the mission and assists alignment of the telescope primary mirror segments . This paper will review significant elements of the mechanical design of the FWA mechanism.

8863-16, Session 4

JWST NIRCam pick-off mirror grounding

Paul V. Mammini, Howard P. Demroff, James Mathieson, Brian B. Jones, Michael Jacoby, Yalan Mao, Lockheed Martin Space Systems Co. (United States)

The optics train of the Near Infrared Camera (NIRCam) instrument for NASA's James Webb Space Telescope (JWST) includes a Pick Off Mirror (POM) with a view of the L2 space environment. A technique to ground the mirror and remove accumulated charge has been qualified and implemented on the Mod A and B POM. This paper will provide an overview of the qualification process including cryogenic resistance and surface error measurements as well as vibration testing. To measure the efficiency of this technique, a POM engineering model was exposed to representative Mission electron fluence and results with the POM grounded and ungrounded will be presented.

8863-18, Session 4

The GAIA basic angle monitoring system: cryogenic aspects

Ben C. Braam, Wim L. Gielesen, Dick de Bruijn, Teun C. van den Dool, Fred Kamphues, Ellart A. Meijer, TNO (Netherlands)

The GAIA mission will create an extraordinarily precise three-dimensional map of more than one billion stars in our Galaxy. The GAIA spacecraft, built by EADS Astrium, is part of ESA's Cosmic Vision programme and scheduled for launch in 2013. GAIA measures the position, distance and motion of stars with an accuracy of 24 micro-arcsec using two telescopes at a fixed mutual angle of 106.5°, named the 'Basic Angle', at 100 K operational temperature. This accuracy requires ultra-high stability, which can only be achieved by using Silicon Carbide for both the optical bench and the telescopes. TNO has developed, built and space qualified the Silicon carbide Basic Angle Monitoring (BAM) on-board metrology system for this mission. The BAM measures the relative motion of GAIA's telescopes with accuracies in the range of 0.5 micro-arcsec. This is achieved by a system of two laser interferometers able to measure Optical Path Differences (OPD) as small as 1.5 picometer rms. Following a general introduction to the GAIA mission, the Payload Module (PLM) and the use of Silicon Carbide as base material, this presentation will address an overview of the challenges towards the key requirements, cryo-design, integration and (cryo)-testing (including space-level qualification) of GAIA BAM.

8864-50, Session PMon

Survey of experimental results in high-contrast imaging for future exoplanet missions

Peter R. Lawson, Jet Propulsion Lab. (United States); Ruslan Belikov, NASA Ames Research Ctr. (United States); Webster Cash, Univ. of Colorado at Boulder (United States); Mark Clampin, NASA Goddard Space Flight Ctr. (United States); Tiffany Glassman, Northrop Grumman Aerospace Systems (United States); Olivier Guyon, The Univ. of Arizona (United States); N. Jeremy Kasdin, Princeton Univ. (United States); Brian D. Kern, Jet Propulsion Lab. (United States); Richard Lyon, NASA Goddard Space Flight Ctr. (United States); Eugene Serabyn, Jet Propulsion Lab. (United States); Dan Sirbu, Princeton Univ. (United States); John T. Trauger, Jet Propulsion Lab. (United States)

We present and compare experimental results in high contrast imaging representing the state of the art in coronagraph and starshade technology. These experiments have been undertaken with the goal of demonstrating the capability of detecting Earth-like planets around nearby Sun-like stars. The contrast of an Earth seen in reflected light around a Sun-like star would be about 1.2 x 10^-10. Several of the current candidate technologies now yield raw contrasts of 1.0 x 10^-9 or better, and so should enable the detection of Earths, assuming a gain in sensitivity in post-processing of a factor of 10. We present results of coronagraph and starshade experiments conducted at visible and infrared wavelengths. Cross-sections of dark fields are directly compared as a function of field angle and bandwidth. The strength and differences of the techniques are compared.

8864-51, Session PMon

Achromatic focal plane mask for exoplanet imaging coronagraphy

Kevin E. Newman, The Univ. of Arizona (United States); Ruslan Belikov, NASA Ames Research Ctr. (United States); Olivier Guyon, Subaru Telescope, National Astronomical Observatory of Japan (United States); Kunjithapatham Balasubramanian, Daniel Wilson, Jet Propulsion Lab. (United States)

Recent advances in coronagraph technologies for exoplanet imaging have achieved contrasts close to 1e-10 at 4 ?/D and 1e-9 at 2 ?/D in monochromatic light. A remaining technological challenge is to achieve high contrast in broadband light; a challenge that is largely limited by chromaticity of the focal plane mask. The size of a star image scales linearly with wavelength. Focal plane masks are typically the same size at all wavelengths, and must be sized for the longest wavelength in the observational band to avoid starlight leakage. However, this oversized mask blocks useful discovery space from the shorter wavelengths.

We present here the design, development, and testing of an achromatic focal plane mask based on the concept of optical filtering by a diffractive optical element (DOE). The mask consists of an array of DOE cells, the combination of which functions as a wavelength filter with any desired amplitude and phase transmission. The effective size of the mask scales nearly linearly with wavelength, and allows significant improvement in the inner working angle of the coronagraph at shorter wavelengths. The design is applicable to almost any coronagraph configuration, and enables operation in a wider band of wavelengths than would otherwise be possible. We include initial results from a laboratory demonstration of the mask with the Phase Induced Amplitude Apodization coronagraph.

8864-52, Session PMon

Pressure and temperature stabilization of an existing Echelle

Anna Brucalassi, Max-Planck-Institut für extraterrestrische Physik (Germany) and Univ.-Sternwarte München (Germany); Frank U. Grupp, Univ.-Sternwarte München (Germany); Liang Wang, Max-Planck-Institut für extraterrestrische Physik (Germany) and Univ.-Sternwarte München (Germany) and National Astronomical Observatories (China); Ralf Bender, Max-Planck-Institut für extraterrestrische Physik (Germany) and Univ.-Sternwarte München (Germany)

FOCES the stabilized Echelle spectrograph of the Wendelstein observatory of Munich University Observatory is intended to be equipped with a frequency comb for highly accurate and precise radial velocity measurements. In this paper of the series we investigate the influence of the CCD camera system thermal control on the stability of the instrument.

8864-53, Session PMon

An advanced fiber link for the test of highly stable frequency comb-spectrograph coupling

Frank U. Grupp, Max-Planck-Institut für extraterrestrische Physik (Germany) and Univ.-Sternwarte München (Germany); Ronald Holzwarth, Menlo Systems GmbH (Germany) and Max-Planck-Institut für Quantenoptik (Germany); Ralf Bender, Max-Planck-Institut für extraterrestrische Physik (Germany) and Univ.-Sternwarte München (Germany)

FOCES the stabilized Echelle spectrograph of the Wendelstein observatory of Munich University Observatory is intended to be equipped with a frequency comb for highly accurate and precise radial velocity measurements. The design of a prototype fiber link allowing stability check and variations of the simultaneous calibration idea is presented with this paper.

8864-54, Session PMon

Precision near-infrared radial velocity instrumentation I: absorption gas cells

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States); Bernie Walp, Gemini Observatory (United States); Samuel L. Crawford, Jet Propulsion Lab. (United States); Sean Lin, California Institute of Technology (United States)

We have built and commissioned gas absorption cells for precision spectroscopic radial velocity measurements in the near-infrared in the H and K bands. We describe the construction and installation of three such cells filled with 13CH4, 12CH3D, and 14NH3 for the CSHELL spectrograph at the NASA Infrared Telescope Facility (IRTF). We have obtained their high-resolution laboratory Fourier Transform spectra, which can have other practical uses. We summarize the practical details involved in the construction of the three cells, and the thermal and mechanical control. In all cases, the construction of the cells is very affordable. We are carrying out a pilot survey with the 13CH4 methane gas cell on the CSHELL spectrograph at the IRTF to detect exoplanets around low mass and young stars. We discuss the current status of our survey, with the aim of photon-noise limited radial velocity precision. For adequately bright targets, we are able to probe a noise floor of ~7 m/s with the gas cell with CSHELL at cassegrain focus. Our results demonstrate the feasibility of using a gas cell on the next generation of near-infrared spectrographs such as iSHELL on IRTF and an upgraded NIRSPEC at Keck.

8864-55, Session PMon

High-contrast imaging testbed design for future space telescopes with segmented apertures

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Searching for nearby habitable worlds with direct imaging and spectroscopy will require a telescope large enough to provide angular resolution and sensitivity to planets around a significant sample of stars. Segmented telescopes are a compelling option to obtain such large apertures. However, these designs have a complex geometry (central obstruction, support structures, segmentation) that makes high contrast imaging challenging. We are developing a new high-contrast imaging testbed at STScI to provide an integrated solution for wavefront control and starlight suppression on complex aperture geometries. To study these questions and understand the ultimate contrast capabilities, we present our approach to minimize the impact of bench optics, in particular with amplitude-induced errors from the propagation of out-of-pupil surfaces. In addition to classical optical design optimization, the approach includes an analytical model based on Talbot propagation and numerical simulations combining Fresnel propagation with wavefront control (e.g. Electric Field Conjugation / Stroke Minimization).

8864-56, Session PMon

Flat field errors and intrapixel sensitivities for nonredundant aperture mask interferometry (AMI) on JWST-NIRISS

Alexandra Z. Greenbaum, Johns Hopkins Univ. (United States)

The James Webb Space Telescope (JWST) is equipped with a 7-hole non-redundant mask on the Near IR Imager and Slitless Spectrograph (NIRISS). Flat field error is likely to limit the contrast of this imaging mode. This can be mitigated by placing calibrator and target on the same pixel. Image plane modeling, using measured sub-pixel sensitivities, enables us to determine the target and calibrator placements to a fraction of a pixel. This is helpful given the barely Nyquist pixel scale on NIRISS and non-uniform sensitivity within the pixel.

8864-57, Session PMon

Could Giovanni Domenico Cassini see the famous division in Saturn's rings?

Julien Lozi, The Univ. of Arizona (United States) and CNES (France) and ONERA (France); Jean-Michel Reess, Alain Semery, Emilie Lhomé, Sophie Jacquinod, Michel Combes, Pernelle Bernardi, Rémi Andretta, Maxime Motisi, LESIA - Observatoire de Paris (France); Laurence Bobis, Emilie Kaftan, Observatoire de Paris (France)

Nowadays, astronomers want to observe gaps in exozodiacal disks to confirm the presence of exoplanets, or even make actual images of these companions. Four hundred and fifty years ago, Giovanni Domenico Cassini did a similar study on a closer object: Saturn. After joining the newly created Observatoire de Paris in 1671, he discovered 4 of Saturn's satellites (Iapetus, Rhea, Tethys and Dione), and also the gap in its rings. He made these discoveries observing through the best optics at the time, made in Italy by famous opticians like Giuseppe Campani or Eustachio Divini. But was he really able to observe this black line in Saturn's rings? That is what a team of optical scientists from Observatoire de Paris - LESIA with the help of Onera and Institut d'Optique tried to find out, analyzing the lenses used by Cassini, and still preserved in the collection of the observatory. The main difficulty was that even if the lenses have diameters between 84 and 239 mm, the focal lengths are between 6 and 50 m, more than the focal lengths of the primary mirrors of future ELTs. The analysis shows that the lenses have an exceptionally good quality, with a wavefront error of approximately 50 nm rms and 200 nm peak-to-valley, leading to Strehl ratios higher than 0.8. Taking into account the chromaticity of the glass, the wavefront quality and atmospheric turbulence, reconstructions of his observations tend to show that he was actually able to see the division named after him.

8864-58, Session PMon

The optical design of CHARIS: an exoplanet IFS for the Subaru telescope

Mary A. Peters, Tyler D. Groff, N. Jeremy Kasdin, Princeton Univ. (United States); Michael W. McElwain, NASA Goddard Space Flight Ctr. (United States); Michael Galvin, Michael A. Carr, Robert Lupton, Gillian Knapp, Timothy Brandt, Markus Janson, James E. Gunn, Princeton Univ. (United States); Olivier Guyon, Frantz Martinache, Nemanja Jovanovic, Masahiko Hayashi, Naruhisa Takato, Subaru Telescope, National Astronomical Observatory of Japan (United States)

High-contrast imaging instrumentation is now capable of imaging and taking spectra of young planets around nearby stars. We present the optical design of the Coronagraphic High Angular Resolution Imaging Spectrograph (CHARIS), a lenslet-based, cryogenic integral field spectrograph (IFS) for imaging exoplanets on the Subaru telescope. The IFS will provide spectral information for 140x140 spatial elements over a 1.75 arcsecs x 1.75 arcsecs field of view (FOV). CHARIS will operate in the near infrared (0.9-2.5 microns) and provide two separate low (R ~ 15) and high (R ~ 60) spectral resolution observing modes. Taking advantage of the adaptive optics systems and advanced coronagraphs (AO188 and SCExAO) on the Subaru telescope, CHARIS will provide sufficient contrast to obtain spectra of young self-luminous Jupiter-mass exoplanets. In this paper we will focus specifically on the details of the

CHARIS optical design and layout. We include a discussion of the design trades and methods for calculating first order IFS design parameters. The paper will contain the CHARIS Zemax layout and an explanation of the components and design choices. We also quantify the noise sources and noise reduction methods. Finally, we draw conclusions concerning the general optimization of the optical design of exoplanet-purposed integral field spectrographs.

8864-59, Session PMon

PISCES: an integral field spectrograph to advance high contrast imaging technologies

Michael W. McElwain, Qian Gong, Karl R. Stapelfeldt, NASA Goddard Space Flight Ctr. (United States); Marshall D. Perrin, Space Telescope Science Institute (United States); Bruce E. Woodgate, Sara R. Heap, George M. Hilton, NASA Goddard Space Flight Ctr. (United States)

We present a novel optical integral field spectrograph (IFS) concept called the Prototype Imaging Spectrograph for Coronagraphic Exoplanet Studies (PISCES). PISCES is a prototype IFS to be used as a facility class instrument within the NASA Exoplanet Exploration Program's High Contrast Imaging Testbed at the Jet Propulsion Laboratory. Integral field spectroscopy is ideal for high contrast imaging because it enables spectral characterization of exoplanet atmospheres and can enhance achieved image contrast by providing multi-wavelength measurements of the target star's chromatic point spread function. PISCES would be the first IFS to demonstrate the challenging performance requirements of a direct imaging of Earth-like exoplanets mission.

We will present the instrument requirements, a baseline design for PISCES, a simulation of its performance, a solution to mitigate spectral crosstalk, experimental verification of our simulator, and the vacuum compatible opto-mechanical design. PISCES would be assembled and tested at the Goddard Space Flight Center (GSFC), and subsequently delivered and integrated into the HCIT facility. The HCIT will be used to verify the PISCES instrument performance, which will validate the PISCES model, and thereby advance the technological readiness of this system. After demonstrating the performance, PISCES will be used to advance other critical high contrast technologies inside the HCIT.

8864-60, Session PMon

Optimal apodizers for the vector vortex coronagraph with on-axis telescopes

Alexis Carlotti, Princeton Univ. (United States); Dimitri Mawet, European Southern Observatory (Chile); Laurent A. Pueyo, Space Telescope Science Institute (United States)

Phase mask coronagraphs such as the vector vortex coronagraph (VVC) are meant to be used with the circular clear aperture of off-axis telescopes, and their performance is greatly reduced when used with on-axis telescopes. A possible solution to that problem consists in apodizing the entrance pupil plane of the coronagraph. Apodizers can be computed by solving a quadratic optimization problem in which the transmission of the apodizer is maximized under the constraint that the intensity of the electric field in the Lyot plane is less than an extremum value that is chosen to be small enough to sufficiently attenuate the starlight in the subsequent image plane. The transmission of the apodizer and the throughput of the system depends on the characteristics of the aperture and of the Lyot stop. We present apodizers optimally designed for the apertures of the Palomar telescope, the VLT, the E-ELT and the AFTA telescope, and for vortex phase masks with a topological charge of 4. Transmissions of 30 to 50% are found for mean contrast of 1e-8. To relax the manufacturing specifications of the vortex phase mask, we also attempt at taking into account the presence of a small Lyot mask in its center.

8864-61, Session PMon

Hybrid coronagraphic design: optimization of complex apodizers

Alexis Carlotti, N. Jeremy Kasdin, Robert J. Vanderbei, A. J. Eldorado Riggs, Princeton Univ. (United States); Laurent A. Pueyo, Space Telescope Science Institute (United States); Tyler D. Groff, Princeton Univ. (United States)

To spectrally characterize Earth-like planets around nearby stars with a coronagraph, an extreme adaptive optics (ExAO) system is mandatory. The correction of the amplitude and phase aberrations in the wavefront on both sides of the image plane and in sufficiently large bandwidths can be done with two deformable mirrors (DM) in a pupil mapping configuration. While this system is primarily intended to correct for aberrations, it can potentially be used to improve the contrast beyond the nominal value set by the coronagraph; the two DMs can be seen as a complex apodizer. In this paper we compute this complex apodization by solving a numerical optimization problem where the amplitude of the real and the imaginary parts of the electric field in the pupil plane are maximized while the intensity of the electric field in chosen regions of the the subsequent image plane is constrained to be less that a chosen extremum. A phase and an amplitude are then associated to the complex transmission of the apodizer. We add a smoothness constraint to the problem so that a single DM can be used to induce this phase. The amplitude of the apodization can be induced by an upstream mirror, as in a PIAA, or with a transmissive apodizer. Its transmission is not binary, however, and this can be a problem in term of manufacturing. A second optimization problem is solved that finds a high-transmission binary equivalent.

8864-62, Session PMon

Techniques for producing pupil-plane and image-plane coronagraph masks

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Masks for high contrast internal and external coronagraphic imaging require various fabrication technologies to address a wide range of needs including gradient amplitude transmission, tunable phase profiles, ultra-low reflectivity, precise small scale features, and low-chromaticity. We present the approaches employed at JPL to produce pupil plane and image plane coronagraph masks, and lab-scale external occulter type masks by combining electron beam, ion beam, deep reactive ion etching, and black silicon technologies with illustrative examples of each.

8864-63, Session PMon

HOMES holographic optical method for exoplanet spectroscopy

Thomas D. Ditto, 3DeWitt LLC (United States)

A novel telescope architecture is proposed specifically for the purpose of taking spectra of exoplanets orbiting stars within 10 pc ("the neighborhood"). The primary objective and the secondary spectrograph are holographic optical elements (HOEs) formed on flat membrane substrates of low areal mass that can be transported on cylinder rolls that are compatible with the payload geometry of delivery vehicles. Ribbon-shaped HOEs of up to 100 x 10 meters are contemplated. Computer models are presented with these dimensions. The models predict resolving power better than 10 mas. Because the primary separates wavelengths, we consider coronagraphs that use the divide and conquer strategy of one wavelength at a time. After delivery at the second Lagrange point, the stowed membranes are unfurled into flat holographic optics positioned in a four part formation spanning 1 km of open space.

8864-66, Session PMon

Wavelength calibration for the Gemini planet imager ifs using its non-redundant mask

Alexandra Z. Greenbaum, Johns Hopkins Univ. (United States)

The Gemini Planet Imager (GPI) Extreme Adaptive Optics Coronagraph (ExAOC) possesses a non-redundant mask (NRM) in its pupil plane. GPI uses an integral field unit spectrograph (IFS) operating at Y, J, H, and K. IFS data is arranged into wavelength slices. Accurate knowledge of the wavelength of each slice of data in this hyperspectral cube is essential. We show that NRM data provide a reliable independent and precise check on the assumed wavelength calibration of the cubes. This data also provides a reliable measure of pupil geometry, which can feed advanced coronagraphic data analysis techniques.

8864-67, Session PMon

Aqueye+: a wavefront sensorless adaptive optics system for narrowfield coronagraph

Enrico Verroi, Univ. degli Studi di Padova (Italy); Tommaso Occhipinti, Ivan Capraro, Adaptica S.r.l. (Italy); Giampiero Naletto, Cesare Barbieri, Univ. degli Studi di Padova (Italy)

We designed and developed Aqueye+, an instrument for the Copernico 182cm Asiago Telescope, with two observations channels. The first allows the use of a ultrafast photometer based on four single photon avalanche photodiodes (SPADs), the second is a channel for stellar coronagraphy based on innovative optical vortices coronagraph system OVC.

The OVC makes use of a phase mask designed to cut out the light of a on-axis target and to let the light from off-axis sources entering the sensor. The target need to be pointed on the center of the phase mask, extreme pointing precision and image stability, as well as the correction of the wavefront deformation induced by atmospheric effects is therefore required. Since the reduction of asymmetries in the target image is critical for the success for faint objects around the central target direct observations, we implemented an adaptive optics (AO) system with a deformable mirror using 32 actuators. The peculiarity of this AO system is that in Aqueye+ there is no wavefront sensors, but the feedback for the deformable mirror is instead given by the photometric channel (PC). The light flux from telescope is split by a dichroic plate, a narrow band around 633nm is reflected towards the OVC while the rest of the light continues through the PC where a pyramid mirror split the beam in 4arms, with a SPAD each.

The adaptive optics system that allows the stabilization of the image and the use of the OVCis described in this paper

8864-68, Session PMon

Laboratory test of a night-time adaptive optics optimized for exoplanet imaging

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The conception of Extreme AO is proposed for exoplanet direct imaging, and the current Extreme AO plans are mainly designed for large telescopes. Here we propose a night-time AO, which is optimized for 2~4-meter telescopes. With our methods of non-common-path error correction and speckle noise nulling, the goal of this night-time AO is to reach Strehl Ratio > 0.8 at near-infrared K band, which enables direct imaging for brown dwarfs and young-hot Jupiters by using a follow-up coronagraph. The night-time AO uses LabVIEW's parallel programming based on a high-performance workstation computer with multi-core CPUs. In this paper, we report the latest results of laboratory testing for the night-time AO and evaluate its performance based on specified sites and telescopes.

8864-69, Session PMon

Holographic spectrograph for space telescope

Thomas D. Ditto, 3DeWitt LLC (United States)

A spectrograph is described which is made with dual Holographic Optical Elements (HOEs) which are identical and parallel to each other. Both optics are collimating transmission HOEs with focal points that are at equal and opposite distances from each other. The identical HOEs are formed by the interference of a plane wave parallel to the grating plane with an off-axis spherical wave originating in the near-field. In playback, a spectrum can be formed from a point source radiator placed at the position of the recording spherical wave. If played back at an arbitrary wavelength other than the recording wavelength, the image exhibits coma. However, the spectrograph can be configured to play back different wavelengths without coma, if sources are adjusted to optimal locations relative to the first HOE. This spectrograph is intended for an unusual configuration where many nearly monochromatic sources of known wavelengths are separately positioned relative to the first HOE. The special application is in a space telescope capable of resolving spectra from habitable planets within 10 pc. HOEs of this type could be fabricated on membrane substrates with a low areal mass and stowable on rolls for insertion into the second Lagrange point. The intended application is for a 50 x 10 meter class primary objective holographic space telescope with 100 x 10 m HOEs in the spectrograph. We present a computer model of the spectrograph and a preliminary experiment that is a proof-of-principle. Experimental results include variations in efficiency and coma over changes in proximity and parallelism between the two HOEs. Experimental results are compared with predictions from theory.

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8864-70, Session PMon

Comparison of simulated contrast performance of different phase induced amplitude apodization (PIAA) coronagraph configurations

Erkin Sidick, Brian Kern, Andreas Kuhnert, Stuart Shaklan, Jet Propulsion Lab. (United States)

One of the High Contrast Imaging Testbed (HCIT) setups at the Jet Propulsion Laboratory (JPL) is a Phase Induced Amplitude Apodization (PIAA) coronagraph. It employs a deformable mirror and a broadband wavefront estimation and control algorithm called Electric Field Conjugation (EFC) to create a "dark hole" in the final focal plane where exoplanets to be found. So far a mean intensity of 5x10-10 has been achieved experimentally in a dark hole in the monochromatic

point-spread function (PSF) with an inner working angle of 2f?/Dsky using a PIAA coronagraph configuration in which the DM was placed downstream of the front end PIAA set. Placing the DM upstream of the front end PIAA sub-system enables the correction of high spatial frequencies before the PIAA remapping carries that information to frequencies higher than Nyquist, allowing a larger outer working angle. Also, using an inverse-PIAA set at the back end enables one to recover a sharp diffraction-limited image over a useful field of view. We have investigated the broadband-contrast performance of several PIAA coronagraph configurations. The structural design of the optical system as well as the parameters of various optical elements used in the analysis are drawn from those of the PIAA/HCIT system that have been implemented with one DM. In this paper, we present the results of these studies.

8864-71, Session PMon

Spectral flattening of supercontinua with a spatial light modulator

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We demonstrate the generation of broad spectra with a flat intensity distribution from originally highly structured supercontinua, obtained with femtosecond pulses in a photonic crystal fiber. This is accomplished by truncating the spectra at a constant level using a liquid crystal based spatial light modulator. The technique is useful for astronomical spectrograph calibration using frequency combs, where it allows to equalize the optical power of the calibration lines. This enables an increased calibration accuracy by maximizing each line's signal-to-noise ratio.

8864-1, Session 1

Patterns of planet occurrence from Doppler and Kepler *(Invited Paper)*

Andrew W. Howard, Univ. of Hawai'i (United States)

The currently observed architectures of extrasolar planetary systems trace the processes of planetary formation and evolution. Until recently, Jovian-size planets provided nearly all of the observational constraints. From Doppler studies, we detect a steeply rising planet mass distribution down to at least 3 Earth-masses for planets orbiting inside of 0.25 AU. The planet size distribution from Kepler also shows a steep rise with decreasing size, but with a plateau in the occurrence rate for 1-2.8 times Earth size. Analyses of the Kepler data support the bottom-up picture of planet formation by core accretion, but also raise new questions about the mechanisms of planet migration, the timing of protoplanetary gas depletion, and the effect of stellar mass on small planet formation. My talk will focus on these occurrence measurements and their interpretation in the context of small planet formation and migration.

8864-2, Session 1

Space mission design for exoplanet imaging *(Invited Paper)*

Dmitry Savransky, Lawrence Livermore National Lab. (United States)

In the next few years, Kepler will constrain the occurrence rates of Earth-radius planets , multiple ground-based exoplanet imagers will begin to provide spectra of self-luminous giant planets and a large number of transit photometry, doppler spectroscopy, microlensing and direct imaging surveys will continuously add to the pool of known exoplanets. We can now look forward to the next step in exoplanet science: direct imaging from space. Over the last decade, there have been a large number of mission concept studies covering a variety of spacecraft architectures, scales and starlight suppression systems. In this paper, I present systematic methods for predicting the expected science yield of different instrument designs, allowing for the direct comparison of different mission concepts. These methods include the selection of target lists, setting of observation rules, and end-to-end simulations of entire surveys. The effects of the assumed planetary distributions are particularly important and I present results consistent with known distributions of physical and orbital parameters, extrapolated from the results of Kepler and multiple radial velocity surveys. I discuss the trades between using internal and external starlight suppression systems (coronagraphs vs. starshades), as well the benefits of including both in one mission. I present the dependence of science yield on telescope scale, focusing in particular on the 2.4 m aperture provided by the Astrophysics Focused Telescope Asset (AFTA). Finally, I discuss how to select specific rules to optimize different classes of surveys, including followups of known planets and searches for Earth-like planets in the habitable zone.

8864-3, Session 1

Implications for future missions of a possible low value of ETA Earth

Alain M. Léger, Institut d'Astrophysique Spatiale (France); Fabien Malbet, Institut de Planétologie et d'Astrophysique de Grenoble (France)

The main question addressed by the Kepler mission is: "What is the mean number of exo-earths and super-earths located in the Habitable Zone (HZ) of solar-like stars?", ?_earth.

The Kepler mission has not yet given its final estimate, but there is already a clear tendency pointing to a low value, possibly between 3 and 10%, but definitely not 100% or so.

We think that such a possible value for ?_earth will necessarily imply the need for an exhaustive census of the Earth-like planets that are actually present around the 300 nearest F,G,K stars, and the characterization of their orbits. If not, the spectroscopic missions would require a very long detection phase that we estimate to ? 93%, to be for nothing. This census can be achieved by a combination of a 20-yr Radial Velocity survey at a 1 m/s accuracy with an astrometric mission of 5 yrs at an extreme accuracy (0.2 ?as).

We will give an estimate of the number of planets that can be studied spectroscopically by missions (i) in the visible (TPF-C, NWO...), and (ii) in the thermal IR (Darwin, TPF-I...). We will also discuss the consequences of descoping these two classes of missions.

8864-4, Session 1

New worlds airship

Webster Cash, Anthony Harness, Ann Shipley, Univ. of Colorado at Boulder (United States); Tiffany Glassman, Steven Warwick, Northrop Grumman Aerospace Systems (United States)

We review the progress on the New Worlds Airship project, which has the goal of suborbitally mapping the Alpha Centauri planetary system into the Habitable Zone in the next few years. We have completed ground tests of starshades on dry lake beds and have shown excellent contrast. We are now attempting to use starshades on hilltops to occult stars and perform high contrast imaging of outer planetary systems like Fomalhaut. We built a precision line of sight position indicator and flew it on a Zeppelin in October (2013). Since the airship provider went out of business we have been redesigning the project to use UAVs instead. We will report on the latest plans at the meeting.

8864-5, Session 1

MESSI: an efficient broadband high contrast high resolution simultaneous multispectral exoplanetary system imager

Brian A. Hicks, Supriya Chakrabarti, TImothy A. Cook, Univ. of Massachusetts Lowell (United States); Christopher B. Mendillo, Boston Univ. (United States); Nikole Lewis, Massachusetts Institute of Technology (United States); Paul A. Bierden, Boston Micromachines Corp. (United States); Jason Martel, Univ. of Massachusetts Lowell (United States)

We present the Monolithic Exoplanetary System Spectral Imager (MESSI) for simultaneous high-contrast visible multispectral direct imaging of exo-Jupiters. MESSI will enable future discovery and eight color characterization of Jupiter-like exoplanets around stars within 10 parsecs. Technological highlights of this program include: 1. Diffraction limited resolution at 350~nm through active optical aberration correction and greater than million-to-one contrast at narrow star separation using interferometry and post-processing techniques; 2. Demonstrating extreme interferometric stability through the use of monolithic optical assemblies in a controlled environment 3. Optimizing multispectral optical throughput beyond the state of the art while minimizing components. The instrument consists of a monolithic nulling interferometer, tip/tilt mounted deformable mirror, wavefront sensor, and pointing/aberration sensor. The MESSI target field of view is simultaneously broken up into eight colors spanning 350-950 nm using an optically contacted, coated set of longpass filters. Following filtering, all bands are relayed to a single detector using two monolithic assemblies of identical focusing mirrors. The aim is to develop a capable instrument with an eye for simplicity and robustness. The program will be focused on designing for operation on a sounding rocket, a unique platform for establishing heritage for high contrast spectral imaging systems that will be used in future satellites.

8864-6, Session 1

Completion of the echo phase 0/A study

Ludovic Puig, Kate Isaak, Martin Linder, Isabel Escudero Sanz, Pierre-Elie Crouzet, Roger Walker, European Space Research and Technology Ctr. (Netherlands)

The Exoplanet Characterisation Observatory (EChO) is an M-class mission candidate within the science program Cosmic Vision 2015-2025 of the European Space Agency. It was selected in February 2011 to enter an assessment phase (phase 0/A). EChO will characterise the atmospheres of a representative sample of known transiting exoplanets found around nearby stars, potentially from giant Hot Jupiters down to Super-Earths orbiting in the habitable zone of M-dwarf stars.

Following the completion of the Concurrent Design Facility study conducted by ESA in June/July 2011, two parallel industrial studies were carried out throughout 2012, and were then extended till August 2013. Similarly, two parallel instrument studies were conducted till mid-2012, following which an Announcement of Opportunity was released and concluded in February 2013 with the selection of a single instrument consortium.

This paper describes the status of EChO upon completion of the system level and instrument studies. It includes a discussion on the evolution of the science and mission requirements, the description of the final preliminary design and performance parameters, as well as programmatic estimates in terms of technology readiness and schedule.

The next step for EChO will consist of passing the Preliminary Requirements Review, followed by the down-selection of a single M3 mission, towards the end of 2013.

8864-8, Session 1

The debris disk explorer: a balloon-borne coronagraph for observing debris disks

Lewis C. Roberts Jr., Geoffrey Bryden, Wesley Traub, Stephen Unwin, John T. Trauger, John E. Krist, James K. Wallace, Jet Propulsion Lab. (United States); Karl Stapelfeldt, NASA Goddard Space Flight Ctr. (United States); Mark Wyatt, Univ. of Cambridge (United Kingdom)

The Debris Disk Explorer (DDX) is a proposed balloon-borne investigation of debris disks around nearby stars. Debris disks are analogs of the Asteroid Belt (mainly rocky) and Kuiper Belt (mainly icy) in our Solar System. DDX will measure the size, shape, brightness, and color of tens of disks. These measurements will enable us to place the Solar System in context. By imaging debris disks around nearby stars, DDX will reveal the presence of perturbing planets via their influence on disk structure, and explore the physics and history of debris disks by characterizing the size and composition of disk dust.

The DDX instrument is a 0.7-m diameter off-axis telescope and a coronagraph carried by a stratospheric balloon. DDX will take high-resolution, multi-wavelength images of the debris disks around tens of nearby stars. Two flights are planned; an overnight test flight within the United States followed by a month-long science flight launched from New Zealand. The long flight will fully explore the set of known debris disks accessible only to DDX. It will achieve a raw contrast of 10^-7, with a processed contrast of 10^-8. A technology benefit of DDX is that operation in the near-space environment will raise the Technology Readiness Level of internal coronagraphs, deformable mirrors, and wavefront sensing and control, all potentially needed for a future space-based telescope for high-contrast exoplanet imaging.

8864-46, Session 1

Exoplanet detection and characterization using combined coronagraphy and sub-UAS astrometry from space *(Invited Paper)*

Eduardo A. Bendek, NASA Ames Research Ctr. (United States); Olivier Guyon, The Univ. of Arizona (United States); Ruslan Belikov, NASA Ames Research Ctr. (United States); S. Mark Ammons, Lawrence Livermore National Lab. (United States)

Combining high-contrast imaging and astrometry in a single space mission would enable efficient detection and characterization of single- and multiple- planetary systems around nearby stars, allowing determination of planetary mass, composition, atmosphere, and system architecture. These science goals can be achieved using a 2m wide-field (>0.1deg2) class telescope equipped with two instruments: a high-performance coronagraph to perform direct imaging, and a wide field camera to achieve sub-microarcsecond astrometric accuracy. However, these measurements are only possible if there are no relative distortion changes between astrometric observations. At sub-microarcsecond

accuracy regime, even space optics suffers from dynamic distortions in the optical system and dominates the error budget. We propose to utilize a diffractive pupil, in which an array of dots on the primary mirror generates polychromatic diffraction spikes in the focal plane to calibrate the dynamic distortions of the optical system. According to simulations, this technique would allow to obtain 0.2microarcsecond single-visit precision astrometric accuracy. In this talk, we present the laboratory results that demonstrate the diffractive pupil concept on wide-field images. We also discuss simulations and experiments performed at the NASA Ames ACE test bed, demonstrating that the diffractive pupil does not affect the coronagraph performance to 2x10-7. Finally, we assess the compatibility of a diffractive pupil telescope with a general astrophysics mission, showing that the spikes do not impact wide-field observations.

8864-9, Session 2

Sphere: complete laboratory performance and prediction for on-sky first light *(Invited Paper)*

Jean-François Sauvage, ONERA (France); Jean-Luc Beuzit, Institut de Planétologie et d'Astrophysique de Grenoble (France)

Direct imaging of exoplanet is one of the most exciting field of planetology today. The light coming from exoplanet orbiting their host star witnesses for the chemical composition of the atmosphere, and the potential biomarkers for life. However, the faint flux to be imaged, very close to the huge flux of the parent star, makes this kind of observation extremely difficult to perform from the ground.

The direct imaging instruments (SPHERE, GPI) are nowaday reaching lab maturity. Such instrument imply the coordination of XAO for atmospherical turbulence real-time correction, coronagraphy for star light extinction, IR Dual band camera, IFS, and visible polarimetry. The imaging modes include single and double difference (spectral and angular).

The SPHERE project is now at the end of AIT phase. This paper presents the very last results obtained in laboratory, with realistic working conditions. These AIT results allows one to predict on-sky performance, that should come within the next weeks after re-installation at Very Large Telescope at Paranal.

8864-10, Session 2

The ZIMPOL high-contrast imaging polarimeter for sphere: system test results

Ronald Roelfsema, ASTRON (Netherlands); Daniel Gisler, ETH Zurich (Switzerland); Johan Pragt, ASTRON (Netherlands); Hans Martin Schmid, Andreas Bazzon, ETH Zurich (Switzerland); Matthew Kenworthy, Leiden Observatory (Netherlands); Carsten Dominik, Univ. van Amsterdam (Netherlands); Andrea Baruffolo, INAF - Osservatorio Astronomico di Padova (Italy); Anthony Boccaletti, Observatoire de Paris (France); Anne Costille, Jean-Luc Beuzit, Institut de Planétologie et d'Astrophysique de Grenoble (France); Kjetil Dohlen, Observatoire Astronomique de Marseille-Provence (France); Mark Downing, European Southern Observatory (Germany); Eddy Elswijk, Menno de Haan, ASTRON (Netherlands); Norbert Hubin, Markus Kasper, European Southern Observatory (Germany); Christoph Keller, Leiden Observatory (Netherlands); Jean-Louis Lizon, European Southern Observatory (Germany); Patrice Martinez, David Mouillet, Institut de Planétologie et d'Astrophysique de Grenoble (France); Alexey Pavlov, Max-Planck-Institut für Astronomie (Germany); Pascal Puget, Institut de Planétologie et d'Astrophysique de Grenoble (France); Bernardo Salasnich, INAF - Osservatorio Astronomico di Padova (Italy); Frans Snik, Leiden Observatory (Netherlands); Christian Thalmann, Univ. van Amsterdam (Netherlands); Francois Wildi, Observatory of Geneva (Switzerland)

SPHERE (Spectro-Polarimetric High Contrast Exoplanet Research) is one of the first instruments which aim for the direct detection from extra-solar planets. SPHERE commissioning is foreseen in 2013 on the VLT. ZIMPOL (Zurich Imaging Polarimeter) is the high contrast imaging polarimeter subsystem of the ESO SPHERE instrument. ZIMPOL is dedicated to detect the very faint reflected and hence polarized visible light (600-900 nm) from extrasolar planets. It is located behind an extreme AO system (SAXO) and a stellar coronagraph. For the sub-system high contrast performance testing we have build a dedicated test setup including a fiber based star-planet simulator, a switching Half Wave Plate and a coronagraph setup. We have measured the polarimetric high contrast performance of several coronagraphs: a Classical Lyot on substrate, a suspended Classical Lyot, a 4 Quadrant Phase Mask and an Apodized Phase Mask. We describe the impact of crucial system parameters (FLC differential aberrations, HWP switching, instrument polarization, detector non-linearity) on the contrast performance. We also present the high contrast results obtained for the fully integrated SPHERE-ZIMPOL system.

8864-11, Session 3

Estimation and compensation of quasistatic aberrations in high-contrast imaging systems with the coronagraphic phase diversity application to the sphere instrument

Baptiste Paul, ONERA (France) and Lab. d'Astrophysique de Marseille (France); Jean-François Sauvage, Laurent M. Mugnier, ONERA (France); Kjetil Dohlen, Observatoire Astronomique de Marseille-Provence (France); David Mouillet, Institut de Planétologie et d'Astrophysique de Grenoble (France); Thierry Fusco, ONERA (France) and Lab. d'Astrophysique de Marseille (France); Jean-Luc Beuzit, Institut de Planétologie et d'Astrophysique de Grenoble (France); Mamadou N'Diaye, Telescope Science Institute (United States); Marc Ferrari, Lab. d'Astrophysique de Marseille (France)

The final performance of current and future instruments dedicated to exoplanet detection and characterization (such as SPHERE on the VLT, GPI on Gemini North or future instruments on the E-ELT) is limited by intensity residuals in the scientific image plane, which originate in uncorrected optical aberrations. After correction of the atmospheric turbulence, the main contribution to these residuals comes from the quasi-static aberrations introduced upstream of the coronagraph.

In order to measure and compensate for these aberrations, we have proposed a dedicated focal-plane sensor called COFFEE (for COronagraphic Focal-plane wave-Front Estimation for Exoplanet detection), which consists in an extension of conventional phase diversity to a coronagraphic system: aberrations both upstream and downstream of the coronagraph are estimated using two coronagraphic focal-plane images, recorded from the scientific camera itself, without any differential aberration.

This communication gathers COFFEE's improvements: the phase estimation is now performed on a pixel-wise map, which, used with a dedicated regularization metric, allows COFFEE to estimate very high order aberrations, making possible to estimate and compensate for quasi-static aberrations with nanometric precision, leading to an optimization of the contrast on the scientific detector. Besides, COFFEE

has been modified so that it can be used with any coronagraphic focal plane mask.

Lastly, we use COFFEE to measure and correct the wavefront on the SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) instrument during its integration phase: COFFEE's estimation is used to compensate for the quasi-static aberrations upstream of the coronagraph, leading to a contrast improvement on the scientific camera.

8864-12, Session 3

ESPRESSO: an exo-Earths hunter for the VLT

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ESPRESSO is the next european exoplanets hunter. It will combine the efficiency of modern echelle spectrograph with extreme radial-velocity precision. It will be installed at Paranal's VLT in order to achieve two magnitudes gain with respect to its predecessor HARPS, and the instrumental radial-velocity precision will be improved to reach cm/s level. We have constituted a Consortium of astronomical research institutes to fund, design and build ESPRESSO on behalf of and in collaboration with ESO, the European Southern Observatory. The project has passed the final design review in May 2013. The spectrograph will be installed at the Combined Coudé Laboratory of the VLT, it will be linked to the four 8.2 meters Unit

Telescopes through four optical "Coudé trains" and will be operated either with a single telescope or with up to four UTs, enabling an additional 1.5 magnitude gain. In exchange of the financial and human effort, the Consortium will be awarded with guaranteed observing time, which will be invested in a common scientific program. Thanks to its characteristics and ability of combining incoherently the light of 4 large telescopes, ESPRESSO will offer new possibilities in many fields of astronomy. Our main scientific objectives are, however, the search and characterization of rocky exoplanets in the habitable zone of quiet, near-by G to M-dwarfs, and the analysis of the variability of fundamental physical constants. In this paper, we will present the scientific objectives, the capabilities of ESPRESSO, the status of the technical development and the project aspects of this facility.

8864-13, Session 3

ESPRESSO front end exposure meter: a chromatic approach to radial velocity correction

Marco Landoni, Marco Riva, INAF - Osservatorio Astronomico di Brera (Italy); Francesco Pepe, Observatory of Geneva (Switzerland); Paolo Conconi, Filippo M. Zerbi, INAF - Osservatorio Astronomico di Brera (Italy); Alexandre Cabral Pereira, Univ. de Lisboa (Portugal); Stefano Cristiani, INAF - Osservatorio Astronomico di Trieste (Italy); Denis Mégevand, Observatory of Geneva (Switzerland)

This paper presents the Espresso Exposure Meter (EM) implementation. ESPRESSO, the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, will be installed on ESO's Very Large Telescope (VLT). The light coming from the Telescope through a Coudè Focus of all the Four Telescope Units (UTs) will be collected by the Front End Unit that provides Field and Pupil stabilization and injects the beams into the Spectrograph fibers. An advanced Exposure Meter system will be used to correct Radial Velocity (RV) obtained from the scientific spectrum for the Earth relative motion.

In this work we will present the performance of an innovative concept for the Exposure Meter system based on a Charge Coupled Device (CCD) with a chromatic approach for the calculation of the Mean Time of Exposure (MTE). The MTE is a crucial quantity used for the correction of RV for the Earth relative motion during the exposure. In particular, splitting the light in 5/7 different chromatic channels on the CCD, we will probe for potential chromatic effects on the calculation of the MTE in each channel and how they could be used in order to perform the correction of RV. The paper is accompanied by a fully described numerical analysis that keeps into view a key performance evaluation for different stellar spectral types (BA to M spectral class).

8864-14, Session 3

Precision near-infrared radial velocity instrumentation II: noncircular core fiber scrambler

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We have built and commissioned a prototype agitated non-circular core fiber scrambler for precision spectroscopic radial velocity measurements in the near-infrared H band. We have collected the first on-sky performance and modal noise tests of these novel fibers in the near-infrared at H and K bands using the CSHELL spectrograph at the NASA InfraRed Telescope Facility (IRTF). We discuss the design behind our novel reverse injection of a red laser for co-alignment of star-light with the fiber tip via a corner cube and visible camera. We summarize the practical details involved in the construction of the fiber scrambler, and the mechanical agitation of the fiber at the telescope. We present radial velocity measurements of a bright standard star taken with and without the fiber scrambler to quantify the relative improvement in the obtainable blaze function stability, the line spread function stability, and the resulting radial velocity precision. We assess the feasibility of applying this illumination stabilization technique to the next generation of near-infrared spectrographs such as iSHELL on IRTF and an upgraded NIRSPEC at Keck. Our results may also be applied in the visible for smaller core diameter fibers where fiber modal noise is a significant factor, such as behind an adaptive optics system or on a small < 1-m class telescope such as is being pursued by the MINERVA and LCOGT collaborations.

8864-15, Session 3

Design of the CHARIS integral field spectrograph for exoplanet imaging

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Princeton University is building an integral field spectrograph (IFS), the Coronagraphic High Angular Resolution Imaging Spectrograph (CHARIS), for integration with the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system. CHARIS will measure spectra of hot Jovian planets in a coronagraphic image across Y, J, H, and K bands. The 80 milliarcsecond inner working angle and high throughput provides access to distant objects where we expect to see young, hot, Jupiter mass planets. SCExAO's coronagraphs and wavefront control system will make it possible to detect companions five orders of magnitude dimmer than their parent star. However, quasi-static speckles in the image contaminate the signal from the planet. In an IFS this also causes uncertainty in the spectra due to diffractive cross-contamination, commonly referred to as crosstalk. Post-processing techniques can subtract these speckles, but they can potentially skew spectral measurements, become less effective at small angular separation, and at best can only reduce the crosstalk down to the photon noise limit of the contaminating signal. CHARIS will address crosstalk effects of a high contrast image through hardware design, which drives the optical and mechanical design of the assembly. The work presented here sheds light on the optical and mechanical considerations taken in designing the IFS to provide high signal-to-noise spectra in a coronagraphic image from and extreme adaptive optics image. The design considerations and lessons learned are directly applicable to future exoplanet instrumentation for extremely large telescopes and space observatories capable of detecting rocky planets in the habitable zone.

8864-16, Session 4

Small-angle, high-contrast exoplanet imaging with the L-band AGPM vector vortex coronagraph now offered at the VLT

Dimitri Mawet, European Southern Observatory (Chile); Olivier Absil, Christian Delacroix, Univ. de Liège (Belgium); Julien H. V. Girard, Julien Milli, Jared O'Neal, European Southern Observatory (Chile); Pierre Baudoz, Anthony Boccaletti, LESIA - Observatoire de Paris (France); Pierre Bourget, European Southern Observatory (Chile); Pontus Forsberg, Uppsala Univ. (Sweden); Frederic J. Gonte Y., European Southern Observatory (Chile); Serge Habraken, Univ. de Liège (Belgium); Mikael Karlsson, Uppsala Univ. (Sweden); Markus Kasper, European Southern Observatory (Germany); Jean Surdej, Univ. de Liège (Belgium)

Context: High contrast imaging has thoroughly combed through the limited parameter space accessible with first-generation ground-based adaptive optics instruments and the Hubble Space Telescope (HST). Only a few objects were discovered, and many non-detections reported and statistically interpreted. The field is now in need of a technological breakthrough.

Aims: We aim at opening a new parameter space in terms of contrast and inner working angle (IWA) with first generation adaptive optics systems such as NACO at the Very Large Telescope, by providing ground-breaking IWA capabilities in the L' band.

Methods: An annular groove phase mask (AGPM) vector vortex coronagraph optimized for the L' band, made out of diamond subwavelength gratings has been manufactured and thoroughly qualified in the lab. It promises high contrast imaging to be reached at very small inner working angle, potentially being the key to a new parameter space.

Results: Here we present the result of the installation and successful on-sky tests of an L'-band AGPM vector vortex coronagraph on NACO. L' band is a sweet spot for high contrast coronagraphy since the planets-to-star brightness ratio is favorable, while Strehl ratio is naturally higher. Moreover the loss of angular resolution at L' is compensated by the smaller IWA of the AGPM.

8864-17, Session 4

Adaptive phase-mask coronagraph with amplitude and phase modulation for high dynamic range synchronous detection: APM2 coronagraph

Pierre Bourget, Dimitri Mawet, Nicolas Schuhler, Pedro Mardones, European Southern Observatory (Chile)

We present a new Adaptive Phase Mask (APM) coronagraph design enabling Amplitude and Phase Modulation control (APM). The extinction control Adaptive Phase mask coronagraph is a recent technique aiming at accommodating both high dynamic and high angular resolution

imaging of faint sources around bright objects. Discriminating faint sources from static speckles is a challenging problem. Our new concept is based on synchronous demodulation that allows high dynamic detection of a faint target immersed in a background. The APM2 uses the coherence of speckles to discriminate them from proper companions, using the mask itself as the electric field modulator. Synchronous detection in the radio frequency range is used to freeze the turbulence and enable the detection of low amplitude signals. The APM2 offers high dynamic range detection and provides a quick tool to quantify the probability of presence of a faint object close to the central star.

8864-19, Session 4

Electric field conjugation with the project 1640 coronagraph

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The Project 1640 instrument on the 200-inch Hale telescope at Palomar Observatory is a coronagraphic instrument with an integral field spectrograph at the back end, designed to find young, self-luminous planets around nearby stars. To reach the necessary contrast for this, the PALM-3000 adaptive optics system corrects for fast atmospheric speckles, while CAL, a phase-shifting interferometer in a Mach-Zehnder configuration, measures the quasistatic components of the complex electric field in the pupil plane following the coronagraphic stop. This field measurement may then be combined with a system model and data taken separately using a white-light source internal to the AO system to correct for both phase and amplitude aberrations. Here, we demonstrate we can create and maintain a half-plane dark hole in the image plane while the spectrograph is taking data, without requiring any additional probe images or other overhead during the science exposure. We outline the procedure, and report on the sensitivity achieved with this system, both in the lab and on the sky.

8864-20, Session 4

Estimate low- and high-order wavefront using P1640 calibrator measurements

Chengxing Zhai, Jet Propulsion Lab. (United States)

P1640 high contrast imaging system on the Palomar 200in Telescope consists of an apodized-pupil Lyot coronagraph, the PALM-3000 adaptive optics (P3K-AO), and P1640 Calibrator (CAL). Science images are recorded by an integral field spectrograph covering J-H bands for detecting and characterizing stellar companions. With aberrations from atmosphere corrected by the P3K-AO, instrument performance is limited mainly by the quasi-static speckles due to non-common path wavefront aberrations for the light to propagate to the P3K-AO wavefront sensor and to the coronagraph mask.

The non-common path wavefront aberrations are sensed by CAL, which measures the post-coronagraph E-field using interferometry, and can be effectively corrected by offsetting the P3K-AO deformable mirror target position accordingly.

Previously, we have demonstrated using CAL measurements to correct high order wavefront aberrations, which is directly connected to the static speckles in the image plane. Low order wavefront, on the other hand, usually of larger amplitudes, causes light to leak through the coronagraph making the whole image plane brighter. Knowledge error in low order wavefront aberrations can also affect the estimation of the high order wavefront.

Even though, CAL senses efficiently high order wavefront aberrations, the low order wavefront front can be infered with less sensitivity.

Here, we describe our method for estimating both low and high order wavefront aberrations using CAL measurements by propagating the post-coronagraph E-field to a pupil before the coronagraph. A dimension reduction technique is used to speed up numerical computation. We present the results from applying this method to both simulated and experiment data.

8864-21, Session 5

High-contrast imaging with a self-coherent camera *(Invited Paper)*

Raphaël Galicher, Univ. of Paris Diderot (France); Pierre Baudoz, Observatoire de Paris (France); Gérard Rousset, Univ. of Paris Diderot (France); Johan Mazoyer, Observatoire de Paris (France)

Direct imaging is the best solution to study exoplanets with long orbital periods but it requires dedicated instruments. The objective is the suppression of the light of the star that is 10^4 to 10^10 times brighter than its planet which is at less than 1”. Coronagraphs can suppress the light but their performance is limited by wavefront aberrations that induce stellar speckles in the science image. In ground telescopes, adaptive optics compensate for most of the atmospheric turbulence but quasi-static aberrations always remain (flexure with pointing, optical aberrations of moving optics, etc). In space, quasi-static aberrations also exist (thermal expansion). In this context, our team developed the self-coherent camera that is used to minimize quasi-static speckles in the science image. The SCC creates a reference beam that interferes with the speckles in a Fizeau scheme and spatially modulates them in the science image. Demodulating the signal, we retrieve the complex amplitude of the electric field in the science image and use a deformable mirror to enhance the contrast in a dark hole. During my presentation, I will present the principle of the SCC and the solution we use to easily implement it to any coronagraph that uses a Lyot stop. Then, I will show laboratory performance with contrasts of a few 1e-8 between 4 and 15 l/D that we obtain on our THD optical bench. Finally, I will talk about solutions that we study and test on the bench to correct for amplitude aberrations and chromatism effects.

8864-22, Session 5

Speckle correction in polychromatic light using the self-coherent camera for the direct detection of exoplanets

Johan Mazoyer, Pierre Baudoz, Raphaël Galicher, Gérard Rousset, LESIA - Observatoire de Paris (France)

Direct detection is a very promising field in exoplanets. It allows the detection of companions with large separation and, allows their spectral analysis. A few planets have already been detected and are under spectral analysis. But the full spectral characterization of smaller and colder planets requires higher contrasts over large spectral bandwidths. Coronagraphs can be used to reach these contrasts, but their efficiency

is limited by wavefront aberrations. These deformations induce speckles, star lights leaks, in the focal plane after a coronagraph. The wavefront aberrations should be estimated directly in the science image to avoid usual limitations by differential aberrations in classical adaptive optics.. In this context, we introduce the Self-Coherent Camera (SCC). The SCC uses the coherence of the star light to produce spatial modulation of the speckles in the focal plane and estimate the associated electric complex field in focal plane. Controlling the wavefront with a deformable mirror, high contrasts have already been reached in monochromatic light with this technique. The performance of the current version of the SCC is limited when widening the spectral bandwidth. We will present a theoretical analysis of these issues and their possible solution. Finally, we will present test bench performance in polychromatic light.

8864-23, Session 5

Experimental study of the low-order wavefront sensor for the high-contrast coronagraphic imager excede

Julien Lozi, The Univ. of Arizona (United States); Ruslan Belikov, NASA Ames Research Ctr. (United States); Glenn Schneider, The Univ. of Arizona (United States); Olivier Guyon, The Univ. of Arizona (United States) and Subaru Telescope, National Astronomical Observatory of Japan (United States); Eugene Pluzhnik, Thomas P. Greene, Fred C. Witteborn, Dana H. Lynch, Paul K. Davis, Sandrine J. Thomas, Eduardo A. Bendek, NASA Ames Research Ctr. (United States); Kevin E. Newman, The Univ. of Arizona (United States); Domenick Tenerelli, Lockheed Martin Space Systems Co. (United States)

The mission EXCEDE (EXoplanetary Circumstellar Environments and Disk Explorer), selected by NASA for technology development, is designed to study the formation, evolution and architectures of exoplanetary systems and characterize circumstellar environments into stellar habitable zones. It is composed of a 0.7 m telescope equipped with a Phase-Induced Amplitude Apodization Coronagraph (PIAA-C) and a 2000-element MEMS deformable mirror, capable of raw contrasts of 1e-6 at 1.2 lambda/D and 1e-7 above 2 lambda/D. One of the key challenges to achieve those contrasts is to remove low-order aberrations, using a Low-Order WaveFront Sensor (LOWFS). An experiment simulating the starlight suppression system is currently developed at NASA Ames Research Center, and includes a LOWFS controlling tip/tilt modes in real time at 1 kHz. The LOWFS allowed us to reduce the tip/tilt disturbances to 1e-3 lambda/D rms, enhancing the previous contrast by a decade, to 8e-7 between 1.2 and 2 lambda/D. A Linear Quadratic Gaussian (LQG) controller is currently implemented to improve even more that result by reducing residual vibrations. This testbed shows that a good knowledge of the low-order disturbances is a key asset for high contrast imaging, whether for real-time control or for post processing.

8864-24, Session 5

Assessing the performance limits of internal coronagraphs through end-to-end modeling

John E. Krist, Jet Propulsion Lab. (United States); Ruslan Belikov, NASA Ames Research Ctr. (United States); Dimitri Mawet, European Southern Observatory (Chile); Dwight Moody, Jet Propulsion Lab. (United States); Laurent A. Pueyo, Space Telescope Science Institute (United States); Stuart Shaklan, John T. Trauger, Jet Propulsion Lab. (United States)

As part of the NASA ROSES Technology Demonstrations for Exoplanet Missions (TDEM) program, we conducted a numerical modeling study of three internal coronagraphs (PIAA, vector vortex, hybrid bandlimited) to understand their behaviors in realistically-aberrated systems with wavefront control (deformable mirrors). This investigation consisted of two milestones: (1) develop wavefront propagation codes appropriate for each coronagraph that are accurate to 1% or better (compared to a reference algorithm) but are also time and memory efficient, and (2) use these codes to determine the wavefront control limits of each architecture. We discuss here how the milestones were met and identify some of the behaviors particular to each coronagraph. The codes developed in this study are being made available for community use.

8864-25, Session 5

HCIT contrast performance sensitivity studies: simulation versus experiment

Erkin Sidick, Stuart Shaklan, John E. Krist, Eric J. Cady, Brian D. Kern, Jet Propulsion Lab. (United States)

Using the High Contrast Imaging Testbed (HCIT) at the Jet Propulsion Laboratory, we have experimentally investigated the sensitivity of dark hole contrast in a Lyot coronagraph for the following factors: 1) Lateral and longitudinal translation of an occulting mask; 2) Bandwidth used in wavefront estimation; 3) Deformable mirror (DM) degrees of freedom vs. dark hole size; 4) Number of dead DM actuators. We have also observed an artificial planet adjacent to the artificial star to determine the ability to extract the planet image from the residual dark hole speckles. We use both MACOS (Modeling and Analysis for Controlled Optical Systems) and PROPER optical analysis programs with full three-dimensional near-field diffraction analysis to model HCIT's optical train and coronagraph.

8864-26, Session 5

Laboratory demonstration of phase induced amplitude apodization (PIAA) coronagraph with better than 10^-9 contrast

Brian D. Kern, Jet Propulsion Lab. (United States); Olivier Guyon, The Univ. of Arizona (United States); Andreas Kuhnert, Albert F. Niessner, Jet Propulsion Lab. (United States); Frantz Martinache, Subaru Telescope, National Astronomical Observatory of Japan (United States); Amir Give'on, Kunjithapatham Balasubramanian, Jet Propulsion Lab. (United States)

We present coronagraphic images from the Phase Induced Amplitude Apodization (PIAA) coronagraph on NASA's High Contrast Imaging Testbed (HCIT) at the Jet Propulsion Lab, showing contrasts of 5x10^-10 averaged from 2-4 lambda/D, in monochromatic light at 808 nm. In parallel with the coronagraph and its deformable mirror and coronagraphic wavefront control, we also demonstrate a low-order wavefront control system, giving 100x rms suppression of introduced tip/tilt disturbances down to residual levels of 10^-3 lambda/D. Current limitations, as well as broadband (10% fractional bandpass) preliminary results are discussed.

8864-27, Session 6

Image analysis with speckles altered by a deformable mirror

Elizabeth J. Young, N. Jeremy Kasdin, Alexis Carlotti, Princeton Univ. (United States)

Quasi-static speckles are one of the main limitations in imaging exoplanets, since the image of a planet looks similar to a speckle. However, speckles are light from the same coherent source, the star, and incoherent with the planet. By moving the deformable mirror after each image, the speckle pattern as seen on the camera changes between images. The change is very small within the full width half max of the planet, so changes in the planet image are minimal. This fundamental coherence property of the speckles (and incoherence with

the planet light) guides us to develop a planet detection method to distinguish a planet from a speckle by taking advantage of a changing speckle pattern. We present a method of changing the deformable mirror actuator pattern to create a series of images with a changing speckle pattern. These images are then analyzed using our previously developed planet detection algorithm, which conducts a Bayesian hypothesis test of multiple images presuming an independent source of aberrations between images. We present results using a 12 by 12 Boston Micromachines deformable mirror in the Exoplanet Direct Imaging Testbed at Princeton University.

8864-28, Session 6

Demonstration of symmetric dark holes using two deformable mirrors at the high-contrast imaging testbed

A. J. Eldorado Riggs, Tyler D. Groff, Alexis Carlotti, N. Jeremy Kasdin, Princeton Univ. (United States); Eric J. Cady, Brian D. Kern, Andreas Kuhnert, Jet Propulsion Lab. (United States)

The High Contrast Imaging Laboratory (HCIL) at Princeton has developed several important algorithms and technologies for space-based coronagraphy missions to detect earth-like exoplanets. The HCIL is currently the only facility with two deformable mirrors (DMs) in series for focal plane wavefront control, which allows for symmetric dark holes in the image plane. Starting in June 2013, the High-Contrast Imaging Testbed (HCIT) at JPL will have installed two similar deformable mirrors. In this paper we report on the results of our Technology Development for Exoplanet Missions project to verify contrasts of better than 1e-9 in two symmetric dark holes using a shaped-pupil coronagraph at the HCIT. Our previous experiment with a shaped pupil (SP) coronagraph at the HCIT in 2007 yielded single-sided dark holes. That experiment utilized an iterative, least-squares wavefront estimator and the Electric Field Conjugation algorithm for wavefront control. Our current experiment uses the faster Kalman filter estimator and the Stroke Minimization control algorithm to create symmetric dark holes. For tests in 10% broadband light, we use the Windowed Stroke Minimization algorithm to extrapolate estimates of bounding wavelengths from the exposures of the central one. We use the same ripple-style SPs as in the previous HCIT experiment because that mask manufacturing technique proved successful. Our tests of symmetric dark holes in monochromatic and 10% broadband light at the HCIT demonstrate the steady improvements being made by Princeton toward a space-based coronagraphy mission.

8864-29, Session 6

MEMS deformable mirror CubeSat testbed

Kerri L. Cahoy, Anne Marinan, Matthew Webber, Benjamin Novak, Caitlin Kerr, Massachusetts Institute of Technology (United States); Ruslan Belikov, NASA Ames Research Ctr. (United States); N. Jeremy Kasdin, Princeton Univ. (United States); Eduardo A. Bendek, NASA Ames Research Ctr. (United States); Frantz Martinache, Subaru Telescope, National Astronomical Observatory of Japan (United States)

To meet the high contrast requirement of 1 ? 10^?10 to image an Earth-like planet around a Sun-like star, space telescopes equipped with coronagraphs require wavefront control systems. Deformable mirrors (DMs) are a key element of a exoplanet direct imaging wavefront control system, as they correct for optical imperfections, thermal distortions, and diffraction that would otherwise corrupt the wavefront and ruin the contrast. However, the high-actuator count microelectromechanical system (MEMS) deformable mirrors needed for this task have yet to fly in space for a period of time long enough to characterize their on-orbit performance and reduce risk by developing and operating their supporting software and hardware systems. The goal of the MEMS Deformable Mirror CubeSat Testbed is to develop a CubeSat-scale flight-like hardware, software, and remote operation demonstration of MEMS deformable mirror and wavefront sensing technology. The goal is to test the ability of a MEMS deformable mirror to perform wavefront control on-orbit using a CubeSat platform, because of the increasingly straightforward and cost-effective access to space for CubeSats and the ability to characterize performance over a longer mission lifetime than suborbital sounding rockets. At least two MEMS deformable mirrors and drivers will fit in a CubeSat as commercial off-the shelf parts that require only minor modifications, and their mirror technology is identical to their higher actuator-count siblings that could be selected for an exoplanet direct imaging mission. The testbed could be modified to test other small form-factor mirror technologies as well. The wavefront sensing technology that would be developed and evaluated as part of this demonstration to characterize on-orbit mirror performance includes sensorless wavefront sensing (e.g. masks, diversity), as well as more traditional Shack-Hartmann and interferometric approaches. After development, functional, and environmental testing, we expect that the CubeSat-scale MEMS deformable mirror and wavefront sensing payload in addition to the supporting CubeSat subsystems (attitude control, command and data handling, communications, thermal, and power) that comprise the laboratory testbed would be ready for launch. Characterizing MEMS deformable mirror devices and simple wavefront control algorithms over months in space on a CubeSat would establish on-orbit heritage and would be valuable inputs to the scientists, engineers, and mission planners for a dedicated exoplanet direct imaging space telescope mission.

8864-30, Session 6

Planar waveguide integrated spatial filter array

Jun Ai, Fedor Dimov, Luminit LLC (United States); Richard Lyon, NASA Goddard Space Flight Ctr. (United States); Neven Rakuljic, Chris Griffo, Xiaowei Xia, Engin Arik, Luminit LLC (United States)

An innovative integrated spatial filter array (iSFA) was developed for the nulling interferometer for the detection of Earth-like planets and life beyond our solar system. The coherent iSFA comprised a 2D planar lightwave circuit (PLC) array coupled with a pair of 2D lenslet arrays in a hexagonal grid to achieve the optimum fill factor and throughput. The silica-on-silicon waveguide mode field diameter and numerical aperture (NA) were designed to match with the Airy disc and NA of the microlens for optimum coupling. The lenslet array was coated with a chromium pinhole array at the focal plane to pass the single-mode waveguide but attenuate the higher modes. We assembled a 30 by 30 array by stacking 30 chips that were produced by photolithography from a 6 in. silicon wafer. Each chip has 30 planar waveguides. The PLC array is inherently polarization-maintaining (PM) and requires much less alignment in contrast to a fiber array, where each PM fiber must be placed individually and oriented correctly. The PLC array offers better scalability than the fiber bundle array for large arrays of over 1,000 waveguides. This project is sponsored by NASA contract NNX-10-C-A56C.

8864-18, Session 7

Improving image contrast for the direct detection of exoplanets at small inner working angles

Sandrine J. Thomas, Ruslan Belikov, NASA Ames Research Ctr. (United States); Laurent A. Pueyo, Space Telescope Science Institute (United States); Eugene Pluzhnik, NASA Ames Research Ctr. (United States); Julien Lozi, The Univ. of Arizona (United States)

The detection of extrasolar planets, using both space- and ground-based telescopes, is one of the most exciting fields in astronomy today. The ultimate goal that we all work towards is to directly image exoplanets and potentially directly detect planets in the habitable zone. It is with this vision that the explorer mission EXCEDE selected by NASA for technology development, is designed. EXCEDE (Exoplanetary Circumstellar Environment and Disk Explorer) is composed of a 0.7 m telescope equipped with a Phase-Induced Amplitude Apodization Coronagraph (PIAA-C) and a 2000-element MEMS deformable mirror, capable of raw contrasts of 1e-6 at 1.2 lambda/D and 1e-7 above 2 lambda/D. To obtain such contrasts requires precise wavefront control algorithms using deformable mirrors. Unlike other optical systems where the goal is to obtain the best wavefront, we aim at canceling the diffracted light coming from the parent star to increase the signal coming from the planet. To do so, we use wavefront control techniques, such as Electric Field Conjugation (EFC) and stroke minimization, already developed and soon be operational on 8-m class telescopes. One caveat is that they primarily function at moderate separations (r>3 lambda/D). In this paper, we present variants of EFC that aim at canceling on-axis diffracted light close to the parent star in order to increase our discovery region. We will use the NASA Ames Coronagraphic Experiment (ACE) testbed to test these algorithms.

8864-31, Session 7

EXCEDE technology development II: demonstration of high contrast at 1.2 L/D and first broadband results

Ruslan Belikov, Eduardo A. Bendek, Thomas P. Greene, NASA Ames Research Ctr. (United States); Olivier Guyon, Julien Lozi, The Univ. of Arizona (United States); Dana H. Lynch, NASA Ames Research Ctr. (United States); Kevin E. Newman, The Univ. of Arizona (United States); Eugene Pluzhnik, NASA Ames Research Ctr. (United States); Glenn Schneider, The Univ. of Arizona (United States); Domenick Tenerelli, Lockheed Martin Space Systems Co. (United States); Sandrine J. Thomas, Fred C. Witteborn, NASA Ames Research Ctr. (United States)

Coronagraph technology is advancing and promises to enable space telescopes capable of directly detecting low surface brightness circumstellar debris disks as well as giant planets as close as in the habitable zones of their host stars. One mission capable of doing this is called EXCEDE (EXoplanetary Circumstellar Environments and Disk Explorer), which in 2011 was selected by NASA's Explorer program for technology development (Category III). EXCEDE is a 0.7m space telescope concept designed to achieve raw contrasts of 1e-6 at an inner working angle of 1.2 l/D and 1e-7 at 2 l/D and beyond. In addition to doing fundamental science on debris disks, EXCEDE will also serve as a technological and scientific precursor for an exo-Earth imaging mission. EXCEDE uses a Starlight Suppression System (SSS) based on the Phase Induced Amplitude Apodization (PIAA) coronagraph to provide high throughput and high contrast close to the diffraction limit, enabling aggressive performance. We report on our continuing progress of developing the SSS for EXCEDE, including (a) high contrast performance demonstrations at 1.2 l/D, which includes a lab demonstration of 8e-7 contrast at 1.2 l/D, 2e-8 at 2 l/D in monochromatic light at 655nm, and a preliminary 10% broadband result of 6e-6 contrast at 1.2 l/D; (b) the installation of a new Low Order Wavefront Sensor (LOWFS) which enabled achieving deep contrasts at aggressive inner working angles; (c) implementation of more efficient model-based wavefront control algorithms; and (d) preliminary demonstrations of new focal plane masks achieving better broadband performance than standard hard-edge masks.

8864-32, Session 7

High-contrast imaging with the vortex coronagraph

Eugene Serabyn, Jet Propulsion Lab. (United States); Dimitri Mawet, European Southern Observatory (Chile); John T. Trauger, Dwight Moody, Kurt Liewer, John E. Krist, Brian D. Kern, Jet Propulsion Lab. (United States)

The vortex coronagraph has great potential for enabling high-contrast observations very close to bright stars, and for reducing the size of space telescopes needed for exoplanet characterization. Here we discuss recent progress in vortex coronagraphy, including the production of vector vortex masks ,and their measured contrast performance. Monochromatic contrasts of 1e-9 have recently been demonstrated, and broadband operation is the next step. Development of broadband vortices should enable their use on future space-based coronagraphic instruments and missions.

8864-33, Session 8

High-contrast imaging with an arbitrary aperture: active correction of aperture discontinuities *(Invited Paper)*

Laurent A. Pueyo, Colin Norman, Johns Hopkins Univ. (United States)

We present a new method to achieve high-contrast images using segmented and/or on-axis telescopes. Our approach relies on using two sequential Deformable Mirrors to compensate for the large amplitude excursions in the telescope aperture due to secondary support structures and/or segment gaps. In this configuration the parameter landscape of Deformable Mirror Surfaces that yield high contrast Point Spread Functions is not linear, and non-linear methods are needed to find the true minimum in the optimization topology. We solve the highly non-linear Monge-Ampere equation that is the fundamental equation describing the physics of phase induced amplitude modulation. We determine the optimum configuration for our two sequential Deformable Mirror system and show that high-throughput and high contrast solutions can be achieved using realistic surface deformations that are accessible using existing technologies. We name this process Active Compensation of Aperture Discontinuities (ACAD). We show that for obscured, on-axis of geometries analogous to the Hubble Space Telescope ACAD can reach broadband contrasts of 10^-8 with a variety of coronagraphs. We then discuss the applicability of this technique to future space-based observatories.

8864-34, Session 8

Shaped pupil coronagraphy with the AFTA telescope

Alexis Carlotti, N. Jeremy Kasdin, Robert J. Vanderbei, Princeton Univ. (United States)

The recently completed study of using the AFTA telescopes for a potential WFIRST mission included a coronagraph instrument for exoplanet imaging. The challenge is to design a coronagraph that achieves the desired high contrast in the presence of the complicated on-axis optical architecture of the AFTA. This is especially difficult if contrast levels as small as 1e-9 must be achieved at a few lambda/D from the star. In this paper we present shaped pupil designs using our new two-dimensional formulation. These designs also include constraints given by the wavefront control system, a necessary element of a complete high-contrast system in space. We have computed various shaped pupils for different contrast floors, inner working angles, and high-contrast region shapes. Two main types of masks are presented: discovery masks

that offer wide discovery space with moderate inner working angles, and characterization masks which are designed for narrower discovery space and smaller inner working angles. A discovery mask would be used first to locate potential candidates at shorter wavelengths. Once the location of a planet is known, a characterization mask would be used to measure its spectrum in broadband.

8864-35, Session 8

The ring-apodized and multistage vortex coronagraph: two simple, small-angle coronagraphic solutions for heavily obscured apertures

Dimitri Mawet, European Southern Observatory (Chile); Pierre Baudoz, LESIA - Observatoire de Paris (France); Laurent A. Pueyo, Space Telescope Science Institute (United States); Alexis Carlotti, Princeton Univ. (United States); Bertrand Mennesson, Eugene Serabyn, James K. Wallace, Jet Propulsion Lab. (United States)

The vortex coronagraph is a well-proven new generation coronagraph currently offered or soon to be offered on various 8-meter class telescopes (Palomar, VLT, and soon LBT and Subaru). The current level of performance on ground-based telescopes is not limited by intrinsic properties of the actual vortex devices, but by thermal background and/or partially corrected wavefronts. However, in the particular case of unfriendly apertures (mainly large central obscuration) when very high contrast is needed (second-generation instruments, ELTs, space- based missions), a vortex coronagraph alone can not deliver because of the contamination due to the diffraction from the obscured part of the pupil. Based on remarkable properties of optical vortices, we recently proposed a method, based on the self-similarity of the topological charge 2 Lyot-plane 1/r^2 amplitude distribution, that reduces the residual light leakage of on-axis telescopes to (a/A)^2n, with n, the even number of stages satisfying n ≥ 2, and a and A, the radii of the central obscuration and primary mirror, respectively. This method was a first step towards enabling high contrasts with an on-axis telescope. However, when the central obscuration exceeds 20%, or if very high contrast is needed, the number of stages required might become prohibitive. In this paper, we present two simple optical solutions to alleviate this issue: (i) We first show that a simple single-stage ring apodizer, exploiting the self-similarity of the vortex Lyot-plane amplitude distribution, allows perfectly nulling the diffraction from the central obscuration. (ii) A 3-stage VC can restore the vortex full null property for any obscuration geometry.

8864-36, Session 8

Complex apodized Lyot coronagraph for exoplanet imaging with partially obscured telescope apertures

John T. Trauger, John E. Krist, Dwight Moody, Brian Gordon, Jet Propulsion Lab. (United States); Dimitri Mawet, European Southern Observatory (Chile)

We update the design, fabrication, performance, and future prospects for the complex apodized Lyot coronagraph. We report new circular focal plane mask designs for high-contrast exoplanet imaging and spectroscopy with telescope apertures that are unobscured, centrally obscured, as well as apertures with complicated obscurations such as the AFTA/SALSO reuse telescopes. Together with a pair of deformable mirrors for active wavefront control, the complex Lyot coronagraph provides high contrast dark fields of view extending to within angular separations of 2.5 ?/D from the central star, over spectral bandwidths of 20% or more, and with throughput efficiencies up to 60%.

8864-37, Session 8

Wavefront control scenarios for a coronagraph on the AFTA space telescope

Tyler D. Groff, N. Jeremy Kasdin, Princeton Univ. (United States); Laurent A. Pueyo, Space Telescope Science Institute (United States); Stuart Shaklan, Jet Propulsion Lab. (United States)

A coronagraph on the Astrophysics Focused Telescope Asset (AFTA) provides a unique opportunity to conduct space based spectroscopic characterization of faint planets orbiting nearby stars. The principal components of such an instrument are the coronagraph itself, the integral field spectrograph (IFS) imager, and a wavefront control system to remove observatory instabilities and quasi-static speckles. Such a system will need to reach contrast levels of approximately 1e-9 at small angular separations to detect super-earths and characterize exo-zodiacal light for any future flagship class missions. We perform a sensitivity study to demonstrate the achievable performance using the proposed first-order AFTA instrument hardware and a focal plane wavefront controller with the IFS and a low order wavefront sensor. The wavefront estimation scheme is assumed to be a closed loop Kalman filter estimator, which can provide estimates at multiple wavelengths thanks to the IFS, with an optimal control law sending commands to the DM. The limiting magnitude of the target is driven by the integration time required to achieve adequate signal-to-noise in the estimation step, the detector noise characteristics, and the stability of the observatory. We demonstrate these effects and define observatory stability limits and the performance required from the low-order wavefront sensor by simulating the optical system with appropriate noise and intensity levels. The primary conclusions are centered around detector noise limits, limiting apparent magnitudes for the parent star, observatory stability requirements, and time budgeting required for wavefront control, preferential observational strategies, and post-processing schemes.

8864-38, Session 8

Imaging Earth-like planets around late-type stars with low-inner working angle PIAA coronagraphy

Olivier Guyon, Subaru Telescope, National Astronomical Observatory of Japan (United States)

The phase-induced amplitude apodization (PIAA) technique, by performing lossless apodization, allows high performance coronagraph architectures simultaneously offering low inner working angle and high throughput. The most recent designs, the PIAA complex mask coronagraph (PIAACMC), use a phase-shifting focal plane mask and offer ~1 lambda/D inner working angle on centrally obscured or segmented apertures. Scientifically, this enables direct imaging of potentially habitable rocky planets around the ~20 nearest stars with a 2.4 m diameter telescope in visible light. The optimal targets for this application are early M and K type stars, for which the planet to star contrast is most moderate than for Sun-like stars, and become accessible thanks to the coronagraph's small inner working angle. On the next generation of ground-based extremely large telescopes (ELTs), PIAACMC allows imaging and spectroscopic characterization of habitable planets around nearby M-type stars, for which the planet-to-star contrast, at ~1e-7, is within reach.

8864-39, Session 8

Coronagraph design for the AFTA telescope

Stuart Shaklan, Marc C. Foote, Marie Levine, Jet Propulsion Lab. (United States); J. Michael Rodgers, Synopsys, Inc. (United States); Michael Underhill, Luis Marchen, Daniel B. Klein, Jet Propulsion Lab. (United States)

The Astrophysics Focused Telescope Assets (AFTA) study in 2012-2013 included a high-contrast stellar coronagraph to complement the wide-field infrared survey (WFIRST) instrument. The idea of flying a coronagraph on this telescope was met with some skepticism because the AFTA pupil has a large central obscuration with six secondary mirror struts that impact the coronagraph sensitivity. However, several promising concepts have emerged, and a corresponding initial instrument design has been completed. Requirements on the design include sharing of the Cassegrain field with WFIRST, on-orbit robotic serviceability, operation in a geosynchronous orbit, and room-temperature operation (driven by the coronagraph's deformable mirrors). We describe the optical, mechanical, and thermal properties of the instrument, its operation, its expected performance, and the stability requirements that the coronagraph places on the observatory.

8864-40, Session 8

Starshade Earth characterizer with AFTA/SALSO telescope

P. Douglas Lisman, Jet Propulsion Lab. (United States)

A starshade experiment can leverage the AFTA/SALSO telescope to capture spectra from earthlike exoplanets much earlier and at significantly lower cost than otherwise possible. Demanding telescope requirements, or compromised exoplanet performance, is avoided by suppressing starlight to entering the telescope. Starshades can stow in a compact volume enables a combined launch with the telescope using standard 5 m fairings. Starshade related instrumentation with the telescope is limited, leaving ample resources for a broad range of other experiments. Starshade observation time is limited to less than 20%, while the remaining time is spent repositioning the starshade for the next target star. We present the starshade and occulter system designs and the technology development plan. We also survey potential mission scenarios, including both joint and separate launches. One low-cost separate launch option addressed is to launch as a shared ride to geostationary orbit using an ESPA ring based bus system with the onboard propulsion capability to maneuver to Earth-Sun L2.

8864-41, Session 9

Verifying occulter deployment tolerances as part of NASA's technology development for exoplanet missions

N. Jeremy Kasdin, Princeton Univ. (United States); Stuart Shaklan, Doug Lisman, Mark W. Thomson, David Webb, Eric J. Cady, Jet Propulsion Lab. (United States); Geoffrey W. Marks, Amy Lo, Northrop Grumman Aerospace Systems (United States); Bruce Macintosh, Lawrence Livermore National Lab. (United States)

An external occulter is a satellite employing a large screen, or starshade, that flies in formation with a spaceborne telescope to provide the starlight suppression needed for detecting and characterizing exoplanets. Among the advantages of using an occulter are the broadband allowed for characterization and the removal of light before entering the observatory, greatly relaxing the requirements on the telescope and instrument. In support of NASA's Exoplanet Exploration Program and the Technology Development for Exoplanet Missions (TDEM), we recently completed a 2 year study of the manufacturability and metrology of starshade petals. In this paper we review the results of that successful first TDEM which demonstrated an occulter petal could be built and measured to an accuracy consistent with close to 10^-10 contrast. We then present the results of our second TDEM to demonstrate the next critical technology milestone: precision deployment of the central truss and petals to the necessary accuracy. We show the deployment of an existing deployable truss outfitted with four sub-scale petals and a custom designed central hub. We demonstrate that the system can be deployed multiple times with a repeatable positioning accuracy of the petals better than the requirement of 1.0 mm.

8864-42, Session 9

Achieving high-contrast ratios with a 60-cm starshade

Tiffany Glassman, Suzanne Casement, Steven Warwick, Onur Armagan, Northrop Grumman Aerospace Systems (United States)

The external starshade is a prospective method for the direct detection and spectral characterization of terrestrial planets around other stars, a key goal identified in ASTRO2010. Validation of this approach has been challenging at very small scales (~4 cm) in the lab (e.g. Samuele et al. 2010). We have successfully fabricated 60 cm starshades and begun a series of ground test experiments with them. Our first experiment, limited by city lights and a short (300 m) baseline between the telescope and the starshade, showed excellent light suppression of >10^6. We enhanced our experimental setup to provide longer baselines and reduced aperture size to provide a closer match to the Fresnel number and Inner Working Angle (in ?/D) expected for the flight system. We measured the starshade performance with baselines between starshade and telescope ranging from 0.75 to 1.5 km and demonstrated contrast ratios from ~10^-7 to better than 10^-9, depending on the test conditions and experimental setup. In this paper, we describe the test setup, the reduction techniques, and an analysis of the relevance of these measurements to a flight starshade system.

8864-43, Session 9

Position sensing and control at the Princeton occulter testbed

Dan Sirbu, N. Jeremy Kasdin, Robert J. Vanderbei, Princeton Univ. (United States)

For direct imaging of Earth-like planets, image plane contrast of ten orders of magnitude is required to be achieved through starlight suppression. One promising method for achieving this level of contrast is through the usage of an external occulter, a second spacecraft whose shape is designed through optimization methods to control diffraction and produce deep shadow at the location of the space telescope. At the Princeton Occulter Testbed, we have designed a subscale experiment to verify the numerical diffraction routines used to create optimal occulter shapes and have presented high-contrast imaging results from our testbed. Here we present the design and experimental verification of a new mask designed for high-contrast in the blue portion of the optical spectrum, and designed to leak light at the red end. We demonstrate the feasibility of using such out-of-band diffraction leakage for optical alignment of the occulter and space telescope to enable formation flight.

8864-44, Session 9

Starshade optical edge modeling, requirements, and laboratory tests

Stefan R. Martin, Jet Propulsion Lab. (United States); Siu-Chun Lee, Applied Sciences Lab. Inc. (United States); Eric J. Cady, P. Douglas Lisman, Stuart B. Shaklan, Samuel L. Crawford, Jet Propulsion Lab. (United States)

In conjunction with a space telescope of modest size, a starshade can be used as an external occulter to block light from a target star, enabling the detection of exoplanets in close orbits. Typically, the starshade will be placed some 50,000 km from the telescope and the system oriented so that the sun is on the opposite side of the shade to the telescope, but somewhat away from the line of sight. A small amount of sunlight

can scatter from the edges of the shade directly into the telescope. Since the photon rate from an earthlike exoplanet might be only a few photons per minute, it is desirable that the scattered sunlight is also near this level. We have built an analytical model of the performance of starshade edges for both specular and Lambertian surfaces and derived requirements for properties such as reflectivity and radius of curvature. A computer model was also developed to show the appearance of the sunlight from the starshade and assess the contrast with the exoplanet. We also constructed a Scatterometer with which various test edges were measured and derived the likely performance if used in a starshade. We discuss these models and give the principal results.

The work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

8864-45, Session 10

Astrometric detection of exoplanets from the ground *(Invited Paper)*

Johannes Sahlmann, Observatory of Geneva (Switzerland); Petro F. Lazorenko, National Academy of Sciences of Ukraine (Ukraine); Antoine Mérand, European Southern Observatory (Chile); Didier Queloz, Damien Ségransan, Observatory of Geneva (Switzerland); Julien Woillez, European Southern Observatory (Germany)

Astrometry is a powerful tool to study the populations of extrasolar planets around nearby stars. It gives access to a parameter space not reachable by other observing techniques and is therefore required for obtaining a comprehensive picture of the properties, abundance, and architectures of exoplanetary systems. Ground-based observations with the necessary accuracy of one milli-arcsecond and better are challenging due to turbulence in the Earth's atmosphere and instrumental effects. We will present results from infrared interferometric observations with the VLTI and a programme employing optical imaging with the VLT, both aimed at the astrometric detection of exoplanets. We will discuss these in the context of other ground-based efforts and of GAIA, ESA's astrometry mission scheduled for launch in 2013.

8864-47, Session 10

First experimental results of very high accuracy centroiding measurements for the neat astrometric mission

Antoine Crouzier, Fabien Malbet, Olivier Preis, Francois F. Henault, Pierre Kern, Guillmero Martin, Eric Stadler, Morgan Saint-Pe, Philippe Feautrier, Institut de Planétologie et d'Astrophysique de Grenoble (France); Christophe Cara, Pierre-Olivier Lagage, Commissariat à l'Énergie Atomique (France); Alain M. Léger, Institut d'Astrophysique Spatiale (France); Michael Shao, Renaud Goullioud, Jet Propulsion Lab. (United States)

NEAT is an astrometric mission proposed to ESA with the objectives of detecting Earth-like exoplanets in the habitable zone of nearby solar-type stars. In NEAT, one fundamental aspect is the capability to measure stellar centroids differences at the precision of 5 ? 10?6 pixel.

The NEAT consortium is designing and building a testbed in vacuum in order to demonstrate 5?10?6 pixel precision for the centroid estimation. The goal is to provide a proof of concept for the precision requirement of the NEAT spacecraft. In this paper we give the basic relations and trade-offs that come into play for the design of a centroid testbed and its metrology system. We detail the different conditions necessary to reach the targeted precision and present the characteristics of our current design.

Finally, we will present the experimental results obtained since we began to assemble the bench in February 2013.

8864-48, Session 10

NEAT: an astrometric mission to detect nearby planetary systems down to the Earth mass

Fabien Malbet, Antoine Crouzier, Institut de Planétologie et d'Astrophysique de Grenoble (France); Alain M. Léger, Institut d'Astrophysique Spatiale (France); Michael Shao, Renaud Goullioud, Jet Propulsion Lab. (United States); Pierre-Olivier Lagage, Commissariat à l'Énergie Atomique (France)

High precision astrometry, combined with radial velocity and Gaia's astrometric measurements, has a unique potential to detect and characterize nearby habitable planetary systems. We will present progress on the concept of an high precision astrometric space mission called NEAT that will have the capability to reach the Earth mass limit in the Habitable zone of nearby solar-type stars. We will discuss the scientific objectives of this mission, the technical challenges and also the results of a demonstration that has been performed with the PRISMA satellites flying in formation. The presentation of the experimental test bench that is aimed at demonstrating micro-pixel accuracy measurements will be presented by another paper by Crouzier et al.

8864-49, Session 10

Microarcsec narrowfield astrometry

Michael Shao, Jet Propulsion Lab. (United States)

The focal plane calibration and centroiding experiment consisted of white light images from two single mode fibers focused on to a CCD with a single curved optic. We measured the separation of the two images as the CCD was translated so the images moved ~3 pixel. After appropriate averaging, the rms difference of the separation of the two images was calculated to be 9e-6 lambda/D in both X and Y.

There are many ways to use a diffractive mask to calibrate the field distortion of a telescope. The calibration can be done while making science measurements, or the calibration can be performed every hour or few hours if the system is sufficiently stable. In this experiment, we use a diversity of images to solve for both errors in the diffractive grating and errors in the telescope.

8865-1,

Memorial tribute to astrobiology pioneers Dr. David S. Mckay and academician Georgi Zavarzin

Alexei Yu. Rozanov, Astrobiology Institute, Joint Institute for Nuclear Research in Dubna (Russian Federation); Richard B. Hoover, Athens State Univ. (United States) and Univ. of Buckingham (United Kingdom)

No Abstract Available

8865-2, Session 1

Implications of Curiosity's findings for the Viking labeled-release experiment and life on Mars *(Invited Paper)*

Gilbert V. Levin, Arizona State Univ. (United States)

Curiosity's latest reported findings, or lack thereof, are interpreted from the standpoint of their implications for the Viking Labeled Release experiment, and for life on Mars in general. As of the writing of this abstract, Curiosity has reported no findings related to those anticipated by the author's last year's paper, "Stealth Life Detection Experiments Aboard Curiosity." However, Curiosity scientists have stated that soil and rock samples have been taken and analyzed, and abundant images have been downloaded. The only indirectly relevant reports issued by Curiosity scientists concern small-molecule organics found in a soil sample, which simple compounds might be terrestrial contamination, and images of rocks with colored (green) patches, the latter not of sufficient resolution, of which the cameras are capable, to detect possible evidence of biology. Hopefully, by the time of preparation of the body of this paper, more information will be available.

8865-3, Session 1

On the interpretations of curiosity results as related to the possibility of life on Mars

Vera M. Kolb, Univ. of Wisconsin-Parkside (United States); Richard B. Hoover, Athens State Univ. (United States) and Univ. of Buckingham (United Kingdom)

As the results from the Mars Mission "Curiosity" trickle in, questions about their relevance to the possibility of life on Mars are posed. We review recent reports concerning the distribution of subsurface water in Gale Crater and the possible detection of chloromethane, fluorinated hydocarbons and other organics in view of terrestrial microbiology and implications to the possibility of present day life on Mars. We examine the reductive chlorination in the energy metabolism of anaerobic bacteria on Earth, as potentially relevant to the findings of chlorinated organics on Mars. In addition, we present cases of chlorinated products as metabolic products from some species living in permafrost on Earth. We will discuss also other relevant scenarios, as more results become available from "Curiosity".

8865-4, Session 2

Impact of prebiotic synthesis and diagenesis on the distribution, stereochemistry, and stable isotope composition of amino acids in carbonaceous meteorites *(Invited Paper)*

Michael H. Engel, The Univ. of Oklahoma (United States)

Simulation experiments for prebiotic synthesis result in racemic mixtures (D/L = 1.0) for protein and non-protein amino acids, irrespective of the composition of the precursor gas mixtures or the energy sources employed. It is therefore not surprising that it was commonly assumed that if amino acids in carbonaceous meteorites were formed by similar reactions they would also be racemic. Engel and Nagy (1982) and more recently Glavin et al. (2012) have shown that protein amino acids in carbonaceous meteorites often exhibit a moderate to strong L-amino acid excess (D/L ? 1.0). Engel (1980) hypothesized that this extraterrestrial L-excess might be the precursor material from which life as we know it originated. Stable isotope analyses (e.g. Engel and Macko, 1997) confirmed that the L-amino acid excess in meteorites was indigenous rather than the result of contamination subsequent to impact on Earth.

A key question that arises is that since there are no known mechanisms for the direct prebiotic synthesis of amino acids with an L-enantiomer excess, how did these compounds come to exist in carbonaceous meteorites? It has been proposed (e.g. Engel, 2012 and references therein) that a series of diagenetic reactions subsequent to synthesis are responsible for the L-enantiomer excess. In this paper, this hypothesis is further explored with respect to explaining the range of D/L values for amino acids in the various types of carbonaceous meteorites as well as in different stones of the same meteorite. Possible effects of diagenesis on the stable isotope compositions of these compounds are also addressed.

8865-5, Session 2

Fossilized diatoms in meteorites from recent falls in Sri Lanka *(Invited Paper)*

Richard B. Hoover, The Univ. of Buckingham (United Kingdom) and Athens State Univ. (United States); J. Wallis, Cardiff Univ. (United Kingdom); Daryl H. Wallis, The Univ. of Buckingham (United Kingdom); Keerthi Wickramarathne, Anil Samaranayake, Medical Research Institute Sri Lanka (Sri Lanka); Gregory . Jerman, NASA Marshall Space Flight Ctr. (United States); George Williams, Athens State Univ. (United States); Chandra Wickramasinghe, The Univ. of Buckingham (United Kingdom)

Field Emission and Environmental Scanning Electron Microscopy studies have been carried out on samples from observed meteorite falls in central Sri Lanka. The elemental abundances and mineralogy of the stones and the stable isotope data confirm that these stones are non-terrestrial. Observations of motility and exopolysaccharides with detectable nitrogen content are interpreted as indicating that some of the diatoms were recently living. Freshly fractured interior surfaces of the black stones have also been observed to contain fossilized diatom frustules establishing that these diatoms are indigenous to the meteorite rather than post-arrival contaminants. This was confirmed by the observation that these diatoms were embedded in the meteorite rock matrix and exhibit nitrogen content below the EDX detection limit. The carbon content and mineralogy suggests that these stones may represent a previously ungrouped clan of carbonaceous meteorites with density and mineralogy consistent with data obtained on the nuclei of comets. These observations are interpreted as supporting the Hoyle-Wickramasinghe Panspermia hypothesis and the hypothesis advanced in by Hoover et

al. (Earth, Moon and Planets, 35, 19-45, 1986) that diatoms and other microorganisms might be able to live and grow in comets.

8865-7, Session 2

Physical, chemical, and mineralogical properties of the Polonnaruwa meteorite stones

Jamie Wallis, Cardiff Univ. (United Kingdom); Daryl H. Wallis, Univ. of Buckingham (United Kingdom); Chandra Wickramasinghe, The Univ. of Buckingham (United Kingdom); Richard B. Hoover, Athens State Univ. (United States) and Univ. of Buckingham (United Kingdom)

No Abstract Available

8865-8, Session 2

Acritarchs in carbonaceous meteorites and terrestrial rocks

Alexei Yu. Rozanov, Astrobiology Institute, Joint Institute for Nuclear Research in Dubna (Russian Federation); Richard B. Hoover, Athens State Univ. (United States) and Univ. of Buckingham (United Kingdom)

No Abstract Available

8865-9, Session 2

Comets and entropy hydrodynamics: how does evolution violate the 2nd law?

Robert B. Sheldon, NASA Marshall Space Flight Ctr. (United States)

Darwinian evolution has long proposed that "descent with modification" plus "natural selection" was capable of creating the increasing complexity seen in the fossil record. In the past few decades, computer simulations have been developed to understand the process, using the methods of "genetic algorithms" or codes such as "Ev" or "Avida". The results have been discouraging, suggesting that all the information that arises in such simulations was injected in the rule sets from the outset, and indeed, mathematicians have shown that there cannot be any method that performs better than a random search, if the initial conditions are chosen randomly. This "No Free Lunch" theorem has been interpreted as an outcome of the physical laws of thermodynamics, which say that within closed systems, complexity or "information" cannot increase. This physical result has been applied by cosmologists to the entire universe--a manifestly closed system--to argue that even black holes are not capable of adding or subtracting information. All this leads to the absurd result that we cannot exist, at least, without violating the laws of physics.

We argue instead that information density can increase locally if one is careful to control the flow of entropy. This cannot be done diffusively as many have argued, but can be accomplished through clever use of "invariants of the flow". Since most physics texts discuss simple entropy, they infer unphysical properties of entropy flow as if it were an invariant. But by replacing the entropy with true invariants, it is possible to show how information can be concentrated and "added" in ways that are consistent with the observation of increasing complexity on the Earth. This is analogous to constructing a digital computer out of fluid components, wherein the "calculation" is permitted by clever manipulation of the boundary conditions. Magnetized comets possess exactly the properties needed to produce the simplest invariant, making them a prime candidate for driving evolution. Thus the evolution paradox can be solved, but at the cost of requiring the universe to be in a highly information-dense initial state. Such an initial state must be coherent in order to explain the information density, so that in some sense the universe began "alive".

8865-24, Session 2

Red rain in Sri Lanka *(Invited Paper)*

D. Dhanayake, S. Katugampala, S. Gunasekera, Sri Lanka Institute of Nanotechnology (Sri Lanka); K. Wickrmarathne, Medical Research Institute Sri Lanka (Sri Lanka); A. D. De Silva, Genetech Research Institute (Sri Lanka); K. M. N. De Silva, V. Karunaratne, G. A. J. Amaratunga, Sri Lanka Institute of Nanotechnology (Sri Lanka)

In November 2012 several locations in the North Central province of Sri Lanka were subject to showers of red colour rain. Previously red rain had been reported in the South Indian state of Kerala in 2001 and 2010. Samples of the red rain were subject to detailed analysis. Here we report some of the key results. The 'red' component of the rain arises from planar circular/oval shaped structures with diameters in the range 3 – 10 ?m. Under the optical microscope they have a red-brown coloration and are similar to red blood cells, with an outer wall-like region and in some a central nucleus-like region within it.

However, unlike red blood cells, they do not deteriorate in-vitro and have retained their appearance over what has now been a period of five months. In the scanning electron microscope (SEM) the cell-like structures retain their morphology which is seen at high magnification to have a saucer-like thinner interior with a thick wall-like region. Under energy dispersive X-Ray analysis(EDAX) C, O, N, are the elements detected in the highest abundance with much lower levels of Si, Ca and Al and some trace amounts of Na, K, Mg, Fe and Ti. Analysis of a normal rain sample does not reveal any cell- like structures and contain similar trace levels of Fe, ruling out the possibility of the redness arising from the presence of excessive iron oxide. Additionally atomic absorption spectroscopy (AAS) was carried with hyper-pure chemicals to digest the red rain cell-like structures in order to detect metals below ppm levels. No additional metallic elements were identified, in particular no As, Ag nor U were detected as cited in other reports and analyses of red rain from Sri Lanka1,2.

The most significant difference of the red rain cell-like structures compared to organic terrestrial cells is the inability to detect any phosphorus (P). Detectable levels of P would be expected if DNA were present in a cell nucleus or phospholipids in a cell wall structure. Detailed spatial correlation with elemental analysis in the SEM did not reveal the presence of P in the cell wall like structure, nucleus like localioties or intermediate regions. In comparison, with red blood cells which have similar dimensions but lack a nucleus with DNA, P was detected most probably due to phospholipids in the cell wall. Further chemical tests (Stannous chloride and Vanado molybdate) for P, which are capable of revealing trace amounts below ppm levels, on the red rain cell-like structures also failed to reveal its presence. It should be noted that no staining methods were employed as in the recent work which claims evidence for the presence of DNA in red rain cells from Kerala1. Our analysis was centred on the direct detection of elemental P. These initial results point to the cell-like structures which are found in red rain to be distinct from similar sized red cell structures, such as those from algae, of common terrestrial origin.

1) N. C. Wickramasinghe et al, Journal of Cosmology, (2013), 21(37)

2) N. Miyake et al, Journal of Cosmology, (2013), 22(4)

3) R. Gangappa and S.I. Hogg , Microbiology (2013),159,107-111

8865-10, Session 3

Development of the algorithm for life for the search for extraterrestrial life

Vera M. Kolb, Univ. of Wisconsin-Parkside (United States)

Search for extraterrestrial life is typically based on the assumption that extraterrestrials will have science similar to ours, in particular the knowledge of the electromagnetic theory and its applications. This knowledge could serve as a basis for communication. In contrast, Nicholas Rescher, a philosopher of science, vigorously maintains that the extraterrestrials would be critically different than us, and thus their science would also be different than ours. He presents various arguments to support this idea. If he is correct, the likelihood of communication would be minimal. We critically review his arguments and offer a chemical counterargument. We propose functional equivalents of the key chemical processes in life on Earth. These algorithms would accommodate different chemistry, but functionally the same, elsewhere. Thus, we would expect aliens to be substantially similar to us, and this could then extend to their science as well.

8865-11, Session 3

On the role of the molecular recognition principles in astrobiology

Vera M. Kolb, Univ. of Wisconsin-Parkside (United States)

Chemical evolution operates in various extraterrestrial media. Limited observations have been made of small molecules in the space, comets and meteorites. Complex molecules which are precursors of life on Earth have not yet been observed. However, such molecules may be ubiquitous in the universe, based on some universal physico-chemical principles.

We propose that principles of molecular recognition, which include both intra- and inter-molecular non-covalent interactions, guide syntheses of complex molecules. These principles have been studied in drug-receptor interactions, protein folding and chemical self-assembly, for example. We categorize and apply these principles to selected examples that are relevant to astrobiology.

8865-12, Session 3

Potential alternate life biochemistries

Gregory A. Konesky, K-Plasma Ltd. (United States)

Life on Earth is based on the element carbon which currently is the fourth most abundant element in the cosmos, and also requires liquid water, which is composed of hydrogen and oxygen, the first and third most abundant elements, respectively. However, our present understanding of carbon-based life also requires a number of other elements which are not particularly abundant. Phosphorous, for example, is necessary for DNA and ADP/ATP energy carriers. Elemental abundance alone may not be the only prerequisite for the foundations of life. Furthermore, the abundance ratio of silicon to carbon is approximately 925:1 in the Earth's crust.

We briefly review common carbon-based metabolic pathways and then consider alternate elemental substitutions for the carbon "backbone" and their advantages and difficulties. Other considerations include simple substitutions for some of the additional elements of carbon-based life such as selenium or tellurium for sulfur, or arsenic for phosphorus, which has been the subject of recent research. Alternate terminal electron acceptors are also discussed. Storage and transfer of genetic information, another basic requirement of life, is also considered in terms of elemental substitution.

A fundamental issue of life detection, whether based on carbon or not, relates to life's ability to modify its environment and alter equilibriums, both locally and globally. However, we consider how alternate metabolic rates, operating on vastly different time scales, may complicate detection.

In an extreme speculative example of "life as we don't (yet) know it," dusty plasma lattices are discussed which have shown the ability to self-organize and "reproduce."

8865-13, Session 4

Three-dimensional modeling of evolution of life *(Invited Paper)*

Elena V. Pikuta, Athens State Univ. (United States)

In our previous work, the model of Evolution of Life was constructed based on the data from Archaea, as the most limiting life groups. Geometry of the coordinates for physiological optima of Archaea demonstrated the function of a hyperbola in two dimensions, and of a hyperboloid in three dimensions modeling. It was shown that the hyperboloid has an inclination of 22.5 o. In previous work, both hyperboloids (one- and two-sheet) were positioned vertically, as schematic data for a preliminary result's demonstration.

In this work, we have constructed a hyperboloid with respect to the precise coordinates of physiological groups, and we have added the data for other key groups of microorganisms that interfered and co-evolved with relic groups of Archaea. Consequently, the inclined hyperboloid was composed to demonstrate the evolution of microorganisms in space and time. Here, we present a complete model of the Evolution of Life, discuss interpretation of results, and outlining major conclusions about evolution of the central biological groups on Earth.

In this article, we discuss some critical changes of geometry for separate physiological groups during evolution, and we present conjectures regarding the impact of major environmental cataclysms and climate changes on Earth.

8865-14, Session 4

Elongation Factor-Tu (EF) proteins structural stability and bioinformatics in ancestral gene reconstruction

Sunil Dehipawala, Todd Holden, George Tremberger Jr., David Lieberman, Tak D. Cheung, Queensborough Community College (United States)

A recent paleo-experimental evolution report suggested that the insertion of an ancient version of Elongation Factor-Tu (EF) in E-coli would give rise to mutations of other genes while the inserted ancient sequence has remained intact without mutation. Knowing that EF proteins show strong thermostability via structural divergence and adapt readily to the host organism operating temperatures, the correlations of the thermo-adaptability with the associated DNA sequence bioinformatics have been studied. Fractal dimension via the Higuchi fractal method and Shannon entropy of the DNA sequence classification could be used in a 2-D map as a simple summary. The identification of adaptive selection using entropy marker and functional-structural diversity using fractal dimension would support a regression analysis where the coefficient of determination would serve as evolutionary pathway marker. Comparisons between genes such as 16S rRNA with EF Tu sequences in this study have accounted for the observed thermostability systematically. The limits of fractal dimension and Shannon entropy could be used to predict the thermostability of extremophiles in astrobiological conditions.

8865-15, Session 4

Assessing fluctuating evolutionary pressure in yeast and mammal by bioinformatics of meiotic protein genetic sequences

Todd Holden, Sunil Dehipawala, George Tremberger Jr., David Lieberman, Tak D. Cheung, Queensborough Community College (United States)

The evolutionary rate co-variation in meiotic proteins has been reported for yeast and mammal using phylogenic branch lengths. The corresponding DNA sequences could be classified as a 2D map of fractal dimension and Shannon entropy. The co-variation assessment using phylogenic branch length was found to be consistent with the 2D map distance, thus opening up the 2D map for assessing fluctuating evolutionary pressure on a fundamental genetic level important for retention and duplication. The identification of adaptive selection using entropy marker and functional-structural diversity using fractal dimension would support a regression analysis where the coefficient of determination would serve as evolutionary pathway marker. Comparisons between yeast with mammal sequences in this study have accounted for the observed fluctuating evolutionary pressure systematically. Convergent and divergent fluctuating evolutionary pressure could be studied with extension to genetic sequences in organisms in astrobiological conditions, with the assumption that the continuation of a book of life would require meiotic proteins and their corresponding DNA sequence bioinformatics everywhere in the universe

8865-17, Session 5

Autofluorescence characteristics of the red rain cells *(Invited Paper)*

Godfrey Louis, Cochin Univ. of Science & Technology (India); A. Santhosh Kumar, Mahatma Gandhi Univ. (India)

Red rain cells are the microscopic biological cells which appear mixed in rain water in large quantity imparting visibly red color to the rain water in a strange event called red rain phenomenon. Our study of this phenomenon which happened in Kerala, India in 2001 has shown that the origin of these cells is possibly extraterrestrial. These cells are not so far successfully identified as any organism known on earth. The cells have unusual property like ability to reproduce at extreme high temperature and the colorless daughter cells cultured from the red cells show unusual autofluorescence characteristics. A similar unusual autofluorescence was also observed in yellow rainwater. In this paper we report the auto-fluorescence characteristics of the original red rain cells. High resolution fluorescence microscopy is employed to study the fluorescence images of the cells under UV-Visible excitation. The results are discussed.

8865-18, Session 5

Analysis of Sri Lankan red rain cells

Norimune Miyake, Takafumi Matsui, Chiba Institute of Technology (Japan); Chandra Wickramasinghe, The Univ. of Buckingham (United Kingdom); Anil Samaranayake, Keerthi Wickramarathne, Medical Research Institute Sri Lanka (Sri Lanka)

We present results of SEM, TEM and fluorescence microscope studies of the red rain cells recovered in Sri Lanka in December 2012. Preliminary analysis reveals the presence of an organism, generally similar to the Kerala red rain cells, that appear to reproduce through a process of internal budding. We are not yet to classify the organism as either a eukaryote or prokaryote on the basis of our tests. Further work is in progress.

8865-19, Session 5

Microorganisms in the coloured rain of Sri Lanka

Anil Samaranayake, Keerthi Wickramarathne, Medical Research Institute Sri Lanka (Sri Lanka); Chandra Wickramasinghe, The Univ. of Buckingham (United Kingdom)

A variety of pigmented microorganisms have been identified in the red, yellow, blue and black rain that fell over Sri Lanka in December 2012 and January 2013. There is tentative evidence for the presence of similar organisms, including diatoms, in meteorites falling over the same time period.

8865-20, Session 6

Horizontal gene transfer *(Invited Paper)*

W. Brigham Klyce Jr., Astrobiology Research Trust (United States)

Horizontal Gene Transfer is the primary means by which prokaryotes acquire new genetic programs. In the past two decades, the importance of HGT for evolution among eukaryotes has become apparent as well. The latest examples of HGT among eukaryotes and the implications that HGT may have for evolution and panspermia will be explored.

8865-21, Session 6

Influence of salts, including amino acids, on the rate and outcome of the in-water prebiotic reactions

Vera M. Kolb, Univ. of Wisconsin-Parkside (United States)

Most prebiotic reactions are hypothesized to have occurred in water. However, most organic compounds are insoluble in water. This has provided a great problem for prebiotic chemistry. Recently, it has been shown that many organic materials which are not soluble in water are still capable of reacting in water, often at faster rates than in the organic solvents. This has provided a new era in the study of the prebiotic reactions. The presence of the inorganic salts and the amino acids was ubiquitous in the aqueous media on the prebiotic Earth. We review the most recent work on the influence of salts on the rate and outcome of two organic reactions, Diels-Alder and multicomponent Passerini reaction, as models for other prebiotic reactions.

8865-22, Session 6

Panspermia: a transformative paradigm with sociological and commercial implications

Camilo Urbina, Univ. de Tarapacá (Chile); Chandra Wickramasinghe, The Univ. of Buckingham (United Kingdom)

Despite the rapidly growing body of evidence that favours a non-terrestrial origin of life and ongoing panspermia, a sometimes fierce resistance pervades the scientific community. Gene sequencing studies carried out in many laboratories over the past two decades indicate that the evolution of higher organisms including Homo sapiens sapiens has involved periodic and recurrent insertions of viral DNA into an evolving line. These viral inserts remain dormant in our genes, and most likely contribute to evolutionary/adaptation potential of organisms. The extension of the process of HGT and gene exchange over a galaxy-wide scale was a prediction of the Hoyle-Wickramasinghe theory of evolution published over 3 decades ago. Adopting the correct origin of life/evolution model is not merely of academic interest; it would have profound and far-reaching implications not only in biotechnology and medical science, but also in reassessing sociological perspectives of ourselves and our connections to the wider universe.

8865-23, Session 6

Galactic evolution and the increasing opportunities for life

Gregory A. Konesky, K-Plasma Ltd. (United States)

Enrico Fermi once looked into the night sky and famously asked "Where are they?" in reference to the apparent lack of obvious indications of advanced extraterrestrial civilizations. As our understanding of astrophysics, and its consequences for the emergence of life, continues to grow, a range of possible answers can be suggested for the question "where are they?" At one extreme, the night sky may indeed be filled with examples of the work of advanced extraterrestrial civilizations, but we ourselves are simply too young a civilization to recognize them as such. Consequently, we construct elaborate "natural" explanations of our observations, using our current understanding of physical laws. Occam's Razor may, on occasion, have two edges.

At the other extreme, the universe is still relatively young. The synthesis of heavy elements in the interior of stars continues to enrich their availability to construct new solar systems with an increasing abundance of rocky terrestrial planets such as our own, and provide increasing opportunities for life to take hold.

We consider the present state of our Milky Way Galaxy and the concept of Galactic Habitable Zones, and then show how stellar evolution will modify the boundaries of this Zone over time. The discovery of extremophiles on this planet, such as Deinococcus radiodurans, may also suggest an extension of those boundaries. The importance of long term stability and resources for the emergence and detection of life over interstellar distances is also considered.

It may well be that we are indeed alone. But not for long.

8866-1, Session 1

MODIS SDSM sun view response simulation and SD degradation-tracking improvements

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MODIS reflective solar bands (RSBs) are calibrated on-orbit using an onboard Solar Diffuser (SD) panel and the SD degradation is tracked by an onboard Solar Diffuser Stability Monitor (SDSM). The SDSM views the sun through a 1.44% attenuation screen during SD calibration. The observed SDSM sun view response has shown unexpected ripples that are as large as 10% of the averaged response. As a result, an alternative approaches was developed to better track SD on-orbit degradation. Meanwhile, a model based on geometric factors and design parameters was developed to simulate the SDSM sun view response from MODIS yaw measurements. It illustrated that the ripples were likely induced by erroneous design parameters or misalignment of the opto-mechanical components involved. The model has been further improved by simulating the SDSM sun view response from the first three-year on-orbit SDSM measurements as well. In this report, the improvements of the model are described and the performance of the model is accessed. The model is compared to another simulation approach which simulates the SDSM sun view response using a spline method. The derived SD degradations using the two different simulations for the sun view responses are also compared.

8866-2, Session 1

On-orbit radiometric stability assessment of MODIS thermal emissive bands using lunar observations

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The MODIS thermal emissive bands (TEB) are calibrated on-orbit on a scan-by-scan basis, with reference to an aboard blackbody (BB) operated at 290K for Terra MODIS and 285K for Aqua MODIS. The evaluation of calibration quality at other temperatures requires independent thermal sources. As a radiometrically stable source, the moon has become more important for the on-orbit calibration of space-borne spectral sensors that have regular lunar observation capability. MODIS observes the moon at almost the same lunar phase through its space view (SV) port approximately every month. The stability of MODIS TEB calibration can be assessed with its lunar observations. In general, the surface temperature of the Moon varies considerably with location and the relative position of the Sun. To overcome the difficulty, in this paper, this assessment is primarily based on the lifelong trending of the highest brightness temperatures retrieved from each lunar observation. The temperatures are assumed stable year by year. The seasonal oscillation of the temperatures is partially corrected with calculated Moon-Sun distances. The highest temperature on the lunar surface is roughly 390K, higher than the saturation temperatures of most TEB bands. For these partially saturated bands, the stability trending is based on the ratios of the highest radiances from unsaturated pixels to the radiances of a reference band with no saturation from the spatially matched pixels. Overall, the lunar trending results show that MODIS TEB bands are stable within ±1K throughout its lifetime at the angle of incidence (AOI) of SV and at temperatures of nearly 100K higher than its BB temperatures used for calibration. Additional discussions are focused on the improvement of the trending methodology and its application to VIIRS TEB trending.

8866-3, Session 1

On-orbit calibration performance of MODIS TDI bands

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The gain coefficients of MODIS bands 13 (667nm) and 14 (678nm) require a treatment different from other reflective solar bands (RSB) due to their time delayed integration (TDI) design and a high-low dual-gain setting. During on-orbit calibration using the onboard solar diffuser (SD) the high-gain output 13H and 14H tend to saturate, thus their gain coefficients are derived from the low-gain output 13L and 14L via a calculated high-to-low scaling ratio. Band 13L/H and 14L/H also saturate during lunar observations thus the lunar gain coefficients are referenced and calibrated against other non-saturated bands. As it also has been observed that the response vs scan-angle (RVS) exhibits noticeable changes with time, a time-dependent RVS calibration algorithm has been developed based on the SD and lunar calibration results to improve the quality of the level 1B (L1B) products. This paper reviews the electronic design and built of band 13 and 14, discusses the details of their SD and lunar calibration as well as the time-dependent RVS algorithms, and presents the long-term performance of the calibration coefficients. The long-term trend shows that the gain change for Terra MODIS band 13 and 14 is significant at 6% and 24%, but more modest for Aqua MODIS band 13 and 14 at 6% and 2%. The ratios 13H/13L and 14H/14L are very stable at the level of 0.1% for both MODIS. For RVS, the long-term change is at the level of 3% for Terra MODIS and about 2% for Aqua MODIS.

8866-4, Session 1

Performance assessment of the clouds and the Earth's radiant energy system (CERES) instruments aboard terra and aqua spacecraft

Susan Thomas, Science Systems and Applications, Inc. (United States); Kory J. Priestley, NASA Langley Research Ctr. (United States); Mohan Shankar, Natividad M. Smith, Science Systems and Applications, Inc. (United States); Norman G. Loeb, NASA Langley Research Ctr. (United States); Dale R. Walikainen, Phillip C. Hess, Science Systems and Applications, Inc. (United States)

Clouds and the Earth's Radiant Energy System (CERES) instruments were designed to measure the reflected shortwave and emitted longwave radiances of the Earth's radiation budget and to investigate the cloud interactions with global radiances for the long-term monitoring of Earth's climate. The three scanning thermistor bolom¬eter sensors on CERES measure broadband radiances in the shortwave (0.3 to 5.0 micrometer), total (0.3 to >100 micrometer) and in 8 - 12 micrometer water vapor window regions. Of the five CERES instruments that are currently in operation, four of the CERES instruments (Flight Models1 through 4) fly aboard Earth Observing System (EOS) Terra and Aqua platforms with two instruments aboard each spacecraft, in 705 KM sun-synchronous orbits of 10:30 AM and 1:30 PM equatorial crossing time.

A rigorous and comprehensive radiometric calibration and validation protocol comprising of various studies was developed to evaluate to calibration accuracy of the CERES instruments. The in-flight calibration of CERES sensors are carried out using the internal calibration module (ICM) comprising of blackbody sources and quartz-halogen tungsten lamp, and a solar diffuser plate known as the Mirror Attenuator Mosaic (MAM). The ICM calibration results are instrumental in determining the changes in CERES sensors' gains after launch from the pre-launch

determined values and the on-orbit gain variations. In addition to the broadband response changes derived from the on-board blackbody and the tungsten lamp, the shortwave and the total sensors show a spectrally dependent drop in responsivity in the shorter wavelegth region below one micron that were brought to light through validation studies. The spectrally dependent changes were attributed to the instrument operational modes and the corrections were derived using the sensor radiance comparisons. This paper covers the on-orbit behavior of CERES sensors aboard the Terra and Aqua spacecraft and the determination of the sensor response changes utilising the in-flight calibration and the radiance measurement comparisons viewing various targets. The corrections for the sensor response changes were incorporated in the radiance calculations of CERES Edition3 data products.

8866-5, Session 1

On-orbit solar calibration methods using the clouds and Earth's radiant energy system (CERES) on-orbit calibration system: lessons learned

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The Clouds and Earth's Radiant Energy System (CERES) scanning thermistor bolometers measure earth-reflected solar and earth-emitted long-wave radiance, at the top- of-the-atmosphere. The bolometers measure the earth radiance in the broadband shortwave solar (0.3-5.0 microns) and total (0.3->100 microns) spectral bands as well as in the 8->12 microns water vapor window spectral band over geographical footprints as small as 10 kilometers at nadir. December 1999, the second and third set of CERES bolometers was launched on the Earth Observing Mission Terra Spacecraft. May 2003, the fourth and fifth set of bolometers was launched on the Earth Observing Mission Aqua Spacecraft. Recently, (October 2011) the sixth instrument was launched on the National Polar-orbiting Operational Environmental Satellite System Preparatory Project (Suomi NPP) Spacecraft. Ground vacuum calibrations define the initial count conversion coefficients that are used to convert the bolometer output voltages into filtered earth radiance. The mirror attenuator mosaic (MAM), a solar diffuser plate, was built into the CERES instrument package calibration system in order to define on-orbit shifts or drifts in the sensor responses. The shortwave and shortwave part of the total-wave sensors are calibrated using the solar radiance reflected from the MAM's. Each MAM consists of baffle-solar diffuser plate systems, which guide incoming solar radiance into the instrument fields of view of the shortwave and total wave sensor units. The MAM diffuser reflecting type surface consists of an array of spherical aluminum mirror segments, which are separated by a Merck Black A absorbing surface, over-coated with SIOx (SIO2 for PFM). Thermistors are located within each MAM plate and the total channel baffle. The CERES MAM is designed to yield calibration precisions approaching .5 percent for the total and shortwave detectors. The Terra FM1 and FM2 shortwave channels and the FM1 and FM2 total channels MAM calibration

8866-6, Session 1

Early trends on the clouds and the Earth's radiant energy system (CERES) flight model 5 (FM5) instrument's performance using in-flight calibration sources

Nathaniel P. Smith, Science Systems and Applications, Inc. (United States)

The Clouds and the Earth's Radiant Energy System (CERES) scanning radiometer is designed to measure the solar radiation reflected by the Earth and thermal radiation emitted by the Earth. Four CERES instruments are already in service; two aboard the Terra spacecraft, launched in 1999; and two aboard the Aqua spacecraft, launched in 2002. A fifth instrument, flight model 5 (FM5), launched in October 2011 aboard the NPP satellite, began taking radiance measurements on January 27th, 2012. The CERES FM5 instrument uses three scanning thermistor bolometers to make broadband radiance measurements in the shortwave (0.3 – 5.0 micrometers), total (0.3 - >100 micrometers) and water vapor window (8 – 12 micrometer) regions. An internal calibration module (ICM) used for in-flight calibration is built into the CERES instrument package consisting of an anodized aluminum blackbody source for calibrating the total and window sensors, and a shortwave internal calibration source (SWICS) for the shortwave sensor. The calibration sources are used to define shifts or drifts in the sensor response over the life of the mission. In order to better understand the sensors adaptation to the space environment, daily internal calibrations were conducted on all three channels for the first week after opening the instrument's main covers. Over the next month, the frequency of internal calibrations was reduced to the standard mission schedule of three total and window channel calibrations per week and one shortwave channel calibration per week. This paper presents the results of FM5 on-orbit internal calibrations, discusses any ground to flight changes, and describes trends in the calibration data.

8866-7, Session 2

Innovative approaches to remote sensing in NASA's Earth system science pathfinder (ESSP) program

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Following recommendations of the National Research Decadal Survey in 2007, NASA's Earth System Science Pathfinder Program introduced the Earth Venture-class (EV) of mission opportunities. EV investigations are competitively selected, PI-led, relatively low cost and narrowly focused in scientific scope. Investigations may address a full spectrum of earth science objectives, including studies of the atmosphere, oceans, land surface, polar ice regions, and solid Earth. EV investigations complement the larger, strategic missions identified by name in the Decadal Survey, and provide flexibility to accommodate scientific advances and new implementation approaches.

EV has three program elements. The EV-Suborbital (EVS) are suborbital/airborne investigations with 5-year duration and managed to NPD 7120.8. The EV-Mission (EVM) element comprises small complete missions launched within 5 years of initiation, managed as Class D missions per NPD 7120.5, and cost-capped at $150M. The EV-Instrument (EVI) element develops spaceborne instruments for flight as missions-of-opportunity (MoO). Instruments are managed according to Class C per NPD 7120.5, limited to 5-year development duration and cost capped at $90M. NASA separately secures and funds the access to space for these instruments.

To ensure the success of EV, the management approach of each element is tailored according to the specific needs of the element. For example, for EVI MoOs NASA employs typical oversight consistent with Class C missions, while for Class D EVM missions, industry best practices may be used. Similarly, for EVS best practices from NASA's science research investigations are employed to minimize overhead while enforcing strong project management principles. This paper will explore the differences in management approaches and the advantage of tailoring to ensure mission success.

8866-8, Session 2

Management approach for Earth venture instruments

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The Earth Venture Instrument (EVI) element of the Earth Venture Program calls for developing instruments for participation on a NASA-arranged spaceflight mission of opportunity to conduct innovative, integrated, hypothesis or scientific question-driven approaches to pressing Earth system science issues.

The Announcement of Opportunity (AO) for EVI-1 stressed the importance of "accommodatibility." Although it was not an evaluation factor, those proposals that proposed an instrument "…with a high probability of being compatible with several potential platforms is more likely to be selected than an instrument with less flexible accommodation and orbit requirements." This approach to the AO leads to a potential broad spectrum of instruments requiring hosting on LEO, GEO, or ISS platforms. In addition to the breadth of host platforms, the Principal Investigators were not limited to NASA only participation. The intent was to encourage input from a broad range of PIs including NASA, other agencies, industry and academia.

The management approach for EVI was developed in advance of the selection of the first instrument and was based on this broad spectrum of potential host platforms and PI organizations. This paper will discuss the variations in management approach as dictated by the numerous potential selections. It will further focus on the specific approach for the EVI-1 selection, Tropospheric Emissions: Monitoring of Pollution (TEMPO), whose PI is from the Smithsonian Astrophysical Observatory, a trust establishment of the United States, and will be hosted on a commercial GEO satellite.

8866-9, Session 2

Management approach for NASA's Earth Venture-1 (EV-1) airborne science investigations

Anthony R. Guillory, Todd C. Denkins, Danette Allen, NASA Langley Research Ctr. (United States)

The Earth System Science Pathfinder (ESSP) Program Office (PO) is responsible for programmatic management of National Aeronautics and Space Administration (NASA) Science Mission Directorate's (SMD) Earth Venture (EV) missions. EV is composed of both orbital and suborbital Earth science missions. The first of the Earth Venture missions is EV-1, which are Principal Investigator-led, temporally-sustained, suborbital (airborne) science investigations cost-capped at $30M each over five years. Traditional orbital procedures, processes and standards used to manage previous ESSP missions, while effective, are disproportionally comprehensive for suborbital missions. Conversely, existing airborne practices are primarily intended for smaller, temporally shorter investigations, and traditionally managed directly by a program scientist as opposed to a program office such as ESSP. ESSP has crafted a management approach for the successful implementation of the EV-1 missions within the constructs of current governance models. NASA Research and Technology Program and Project Management Requirements form the foundation of the approach for EV-1. Additionally, requirements from other existing NASA Procedural Requirements (NPRs), systems engineering guidance and management handbooks were adapted to manage programmatic, technical, schedule, cost elements and risk. The program management approach presented for EV-1 will set the precedent for future suborbital EV missions.

8866-10, Session 2

Class D management implementation approach of the first orbital mission of the Earth Venture series

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A key element of the National Research Council's Earth Science and Applications Decadal Survey called for the creation of the Venture Class line of low-cost research and application missions within NASA (National Aeronautics and Space Administration). One key component of the architecture chosen by NASA within the Earth Venture line is a series of self-contained stand-alone spaceflight science missions called "EV-Mission". The first mission chosen for this competitively selected, cost and schedule constrained, Principal Investigator-led opportunity is the CYclone Global Navigation Satellite System (CYGNSS).

As specified in the selecting Announcement of Opportunity, the Principal Investigator is held responsible for successfully achieving the science objectives of the selected mission and the management approach that he chooses to obtain those results has a significant amount of freedom as long as it meets the intent of key NASA guidance like NPR 7120.5 and 7123. CYGNSS is classified under NPR 7120.5E guidance as a Category 3 (low priority, low cost) mission and carries a Class D risk classification (low priority, high risk) per NPR 8705.4. As defined in the NPR guidance, Class D risk classification allows for a relatively broad range of implementation strategies. The management approach that will be utilized on CYGNSS is a streamlined implementation that starts with a higher risk tolerance posture at NASA and that philosophy flows all the way down to the individual part level. This paper will discuss details of the Class D management approach at Program and Project levels.

8866-11, Session 2

Tropospheric emissions: monitoring of pollution (TEMPO)

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TEMPO has been selected by NASA as the first Earth Venture Instrument. It will measure atmospheric pollution for greater North America from space using ultraviolet/visible spectroscopy. TEMPO measures from Mexico City to the Canadian tar/oil sands, and from the Atlantic to the Pacific, hourly and at high spatial resolution. TEMPO provides a tropospheric measurement suite that includes the key elements of tropospheric air pollution chemistry. Measurements are from geostationary (GEO) orbit, to capture the inherent high variability in the diurnal cycle of emissions and chemistry. The small product spatial footprint resolves pollution sources at sub-urban scale. Together, this temporal and spatial resolution improves emission inventories, monitors population exposure, and enables effective emission-control strategies.

TEMPO takes advantage of a GEO host spacecraft to provide a modest cost mission that measures the spectra required to retrieve O3, NO2, SO2, H2CO, C2H2O2, H2O, aerosols, cloud parameters, and UVB radiation. TEMPO thus measures the major elements, directly or by proxy, in the tropospheric O3 chemistry cycle. Multi-spectral observations provide sensitivity to O3 in the lowermost troposphere, reducing uncertainty in air quality predictions by 50%. TEMPO quantifies and tracks the evolution of aerosol loading. It provides near-real-time air quality products that will be made widely, publicly available.

TEMPO makes the first tropospheric trace gas measurements from GEO, by building on the heritage of five spectrometers flown in low-earth-orbit (LEO). These LEO instruments measure the needed spectra,

although at coarse spatial and temporal resolutions, to the precisions required for TEMPO and use retrieval algorithms developed for them by TEMPO Science Team members and currently running in operational environments. This makes TEMPO an innovative use of a well proven technique, able to produce a revolutionary data set.

TEMPO provides much of the atmospheric measurement capability recommended for GEO-CAPE in the 2007 National Research Council Decadal Survey, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. GEO-CAPE is not planned for implementation this decade. However, instruments from Europe (Sentinel 4) and Asia (GEMS) will form parts of a global GEO constellation for pollution monitoring later this decade, with a major focus on intercontinental pollution transport. TEMPO will launch at a prime time to be a component of this constellation.

8866-65, Session PMon

Impact of hyperspectral sensor spectral resolution and bandwidth on cross-comparison with broadband sensor for reflective solar bands

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A new generation of hyperspectral imagers requires a much high absolute accuracy for reflected solar radiation measurements to better understand climate change. The Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission, a future satellite mission led and developed by NASA and partner organizations, is currently considered to consist of two hyperspectral imagers that cover the reflected solar (RS) and infrared radiation. The design of the CLARREO instrument for the RS region operates from 320 to 2300 nm with 8 nm in spectral resolution and 4 nm in bandwidth. In this study, the sensitivity of various spectral resolution and bandwidths is tested for their impacts on integrated radiances using the relative spectral responses (RSR) of broadband sensors. Our hyperspectral data is based on MODTRAN simulations and SCIAMACHY observations and the RSR data is from those used in MODIS and VIIRS level 1B (L1B) product. The sensitivity is conducted for ocean, desert, snow and cloud. The differences among simulated radiances are examined and used to determine the spectral resolution and bandwidth of future CLARREO-type hyperspectral instrument.

8866-66, Session PMon

Vicarious calibration of S-NPP/VIIRS day-night band

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The Day Night Band (DNB) of the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite launched in October 2011 represents a major advancement in night time imaging capabilities. The primary mission of the DNB is to provide imagery of clouds and other Earth features over illumination levels ranging from full sunlight to quarter moon. In order to cover this extremely broad measurement range, the DNB employs four imaging arrays that comprise three gain stages. The low gain stage (LGS) gain values are determined by solar diffuser data (aka the onboard calibration). The medium and high gain stages (MGS and HGS) cannot be calibrated directly because these gain stages saturate at solar diffuser illumination levels. In operation, the medium and high gain stage values are determined by multiplying the LGS gains by the MGS/LGS and HGS/LGS gain ratios, respectively. To independently verify the radiometric accuracy of HGS of DNB, we perform vicarious calibration of DNB when S-NPP flies above the vicarious site such as Dome C in Antarctic at night and the moon illuminates the site with lunar phase being more than half moon. Lunar spectral irradiance model as a function of Sun-Earth-Moon distances and lunar phase is used to assist the determination of top-of-atmosphere reflectance at vicarious site. The trending of vicariously-derived time series of reflectance is compared with the trending determined from other means such as observations of deep convective cloud and stable light sources.

8866-67, Session PMon

Assessment of the MODIS RSB detector differences using Earth-View targets

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MODIS has 20 reflective solar bands (RSB) with a total of 330 individual detectors. Currently, there are two nearly identical MODIS instruments operating in space: one on the Terra spacecraft launched in December 1999 and another on the Aqua spacecraft launched in May 2002. MODIS reflective solar bands (RSB) are calibrated on-orbit by a system that consists of a solar diffuser (SD) and a solar diffuser stability monitor (SDSM). Near-monthly lunar observations are also used to track the sensor response versus scan angle (RVS) change on-orbit. On-orbit observations show that the changes in the detector response are wavelength, scan-angle and mirror side dependent. This paper provides a comprehensive assessment of the detector-detector calibration differences in the MODIS VIS/NISR spectral bands using the on-board calibrators and earth-view (EV) level 1B (L1B) data products. Different EV targets are analyzed to accommodate the high-gain ocean bands which tend to saturate over land surfaces. The results from this study highlight the necessity of the constant monitoring of the detector-level gain and its change as a function of scan-angle, as implemented in the MODIS Collection 6 (C6) products.

8866-68, Session PMon

The preliminary investigation of in-flight radiometric calibration plan of FORMOSAT-5 remote sensing instrument

Kuo-Hsien Hsu, National Space Organization (Taiwan); Hirokazu Yamamoto, National Institute of Advanced Industrial Science and Technology (Japan)

FORMOSAT-5 is the fourth satellite owned by National Space Organization (NSPO), National Applied Research Laboratory (NARL) of Taiwan. The primary payload of FORMOSAT-5 is a high-spatial-resolution (2meters) optical Remote Sensing Instrument (RSI). FORMOSAT-5 is currently scheduled to be launched in 2014. In the satellite Integration and Testing (I&T) phase, the first set of radiometric parameters of the RSI can be accurately measured in a well-controlled laboratory. However, these pre-flight radiometric parameters are inevitably calibrated on-orbit due to effects such as the outgassing phenomenon in the early stage, and on a longer scale by the radiations that effect both the optical transmission and sensor signal in darkness. Therefore, it is necessary to conduct the in-flight radiometric calibration regularly in order to compensate for this. This paper describes the preliminary investigation of in-flight radiometric calibration plan of the RSI onboard FORMOSAT-5, based on the reflectance- and radiance-based vicarious calibration as well as cross-calibration with other sensors.

8866-69, Session PMon

Energetic balance in the precise uniform light source based on optically connected integrating spheres

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The paper presents the mathematical technique for calculation of the output radiance of the precise uniform light sources which have a form of several or multiple optically connected integrating spheres. The principal advantages of these light sources are high photometric and metrological characteristics. The light source contains several (3 … 11) primary integrating spheres of small diameters which are installed on a secondary integrating sphere of bigger diameter. The initial light sources – halogen lamps or light emitted diodes are installed inside the primary integrating spheres. These spheres are mounted on the secondary integrating sphere. The radiation comes from the primary integrating spheres to the secondary one through diaphragms which diameters can be varied. The secondary integrating sphere has an output aperture where uniform radiance emits. The proposed technique describes how to calculate the fluxes coming from the primary integrating spheres to the secondary one. It takes into account the fluxes multiple times coming from the secondary integrating sphere to the primary ones and again from the primary integrating spheres to the secondary one. This flux exchange introduces the additional part to the output radiance of up to 8 % that is very important for precise calibration. As a result the precise value of the output radiance can be obtained. The proposed light sources can be considered as one of the best candidates for calibration of remote sensing radiometers working in optical range 0.4 – 2.2 mkm.

8866-70, Session PMon

On-orbit spatial characterization of VIIRS using the Moon

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The moon is a very stable source for on-orbit calibration of the space-borne sensors with regular lunar observation capability, such as MODIS on-board the Terra and Aqua satellites and VIIRS on-board the Suomi NPP satellite. The spectral bands of both sensors are located on multiple focal plane assemblies (FPA) and spatially registered in both along-scan and along-track directions. Any mis-registration, or the band-to-band registration (BBR) shift, can deteriorate the quality of the science data products that are composed from multiple spectral bands. In this paper, the VIIRS spatial performance, mainly focusing on its BBR, is characterized using its lunar observations via an approach developed and modified from MODIS lunar BBR characterization. In this approach, the centroids of the lunar images of various bands are calculated and the BBR is determined from the differences of these centroids. Results show that on-orbit change of the BBR has been small for VIIRS VIS/NIR bands since its launch in Oct. 2011. Similarly to MODIS lunar spatial characterization, the centroids of lunar images of various detectors within a band can be used to study the detector-to-detector registration (DDR) shift. Since the detectors within a band are assembled in the along-track direction, the movement of the moon relative to the sensor, especially in the along-scan direction, during lunar calibration must be compensated to get reliable DDR results. Overall, results from this study demonstrate that the lunar approaches developed and applied to MODIS lunar spatial characterization can be effectively applied to VIIRS.

8866-71, Session PMon

Trend analysis of the aerosol optical depth over china using fusion of MODIS and MISR aerosol products via adaptive weighted estimate algorithm

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Atmospheric aerosol play an important role in the climate change, though direct and indirect processes [1]. To evaluate the effects of aerosols on climate it is necessary to estimate their spatial and temporal distributions [2]. Satellite aerosol remote sensing is a developing new technology that may provide good temporal sampling and superior spatial coverage to study aerosols. Since 2000, the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectroradiometer (MISR) have been providing global aerosol products [3]. However, the uncertainties still exist in current satellite aerosol products attributable to the complex surface, cloud contamination, and aerosol models used in the retrieving process [4]. Comparing to AERONET AOD, the larger magnitude and different variation tendency in AOD for both sensors indicate that either individual aerosol product may not be good application over China. Combing multiple sensors is a method to reduce uncertainties and improve observational accuracy. An adaptive weighted estimate algorithm of multi-sensor data fusion was presented, which could adjust the fused sensor's weight in time according to the variation in sensor's variance. The combined AOD product using the fusion method is in better agreement with corresponding AOD from AERONET than single sensor, which illustrate the fusion method performs better applicability in China. The fusion method can reduce uncertainties both sensors and expand the scope of the distribution in AOD. A method of evaluation was applied to detect the significance of the regional aerosol trends. Compared with trend analysis in MODIS and MISR, the combined result is improved by 8.2% and 4.5%, respectively, which is considered as significant with confidence level above 95%. Using the latest ten-year (2002-2011) fusion product, we study the trend analysis of the aerosol optical depth over typical regions in China. The insignificant trend is observed over the whole China. However, AOD regional long-term trends are evident. The increasing trend is found over Jingjintang and Yangtze River Delta, which are highly associated with human activities. The evaluation of trend shows trends are statistically significant with 95% confident level over Jingjintang and Yangtze River Delta.

8866-72, Session PMon

Alternative method for VIIRS Moon in space view process

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The Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (S-NPP) spacecraft was successfully launched on October 28, 2011. Since its nadir aperture door opening on November 21, followed by cryo-cooler door opening on January 18, 2012, the VIIRS instrument has been acquiring the Earth images, both in reflective solar bands (RSB) and thermal emissive bands (TEB). The sensors are calibrated on-orbit by a solar diffuser (SD) and solar diffuser stability monitor (SDSM) system for the RSBs, and a blackbody (BB) for the TEBs. The SDR radiometric calibration is performed by subtracting the detector's space view (SV) dark background digital number (DN) from the Earth view (EV) DN scan by scan. Occasionally, the lunar intrusion into SV will corrupt the true background signals, causing contaminated data if not corrected. The current SDR operational code contains a complex algorithm, due to dual gains and two mirror sides, for background substitution when the Moon appears within the defined space view range. It substitutes SV data by BB view data for RSBs or uses SV data several scans away. The algorithm also leaves the TEBs un-calibrated because the SV data are flagged with fill value. This paper

proposes an alternative method, similar to the one used in MODIS L1B calibration. It utilizes part of the SV data which are useful and valid for background subtraction even when the Moon is in the SV. The SDR test for the code change will be performed and the results presented in the paper.

8866-73, Session PMon

Static concentrator tracking system

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Since the position of the sun will change over time, the light collecting efficiency of the traditional passive concentrator can reach its maximum only in a specific period of time, but it may not be optimal at other time.

In this paper, we propose a Static Concentrator Tracking System. First, the system is to determine when the maximum light collection efficiency of Static Concentrator is. We install a small piece of solar panel on the bottom of the Static Concentrator to collect the light out from the bottom of Static Concentrator because of the reflection of sunlight, and to detect the current value of the transparent solar panels generated by photoelectric conversion through Zigbee to judge the efficiency of light collection. When the value of the current generated by the solar panels becomes higher, it represents Static Concentrator is missing out a lot of sunlight and the light collection efficiency is not high; vice versa.when we detect light collection efficiency is poor, the system searches for the location of the sun through a photo-detector, and Zigbee remote control the Mirror Array to adjust the angle of the sunlight. Static Concentrator is therefore able to achieve its maximum light collection efficiency.

The system has two merits, which is able to achieve maximum light collection efficiency at different times and the power generated by the solar panels can be used for other purposes (Ex: Zigbee power or Nighttime lighting needed).

8866-74, Session PMon

Optical infrastructure for time and frequency transfer in the Czech Republic

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In every country exists a time and frequency laboratory that operates a set of atomic clocks to provide national approximation of UTC time scale. Generally, higher number of these interconnected clocks (Caesium primary standards and Hydrogen masers) improves accuracy and stability of the time scale. The term "interconnection" in this context means that we transfer time scales between them despite of their location at geographically distant places – the common method is a dedicated two-way satellite link or a GPS based system, however utilization of fiber links constantly increases.

Experience with time transfer between Czech and Austrian national time and frequency laboratories, whose regular operation started in August 2011 and achieved better time stability compared with GPS based methods, lead us to design and build national infrastructure for time and frequency transfer – TF-infrastructure.

It will connect six institutes into a star and uses variety of means of transport:

-dark fibers for distances from 0.3km (0.2miles) to 16km (10miles)

-lambdas in single fiber bidirectional transmission system for distance of about 70km (43.5miles)

-lambdas in fiber pair transmission system for distance over 300km (186.5miles)

We achieved passive transmission over single fiber bidirectional system and will verify the stability. Near future plan is to improve time stability (in term of TDEV) in fiber pair transmission system.

8866-12, Session 3

Software engineering processes for class d missions

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Software engineering processes are often seen as anathemas; thoughts of CMMI key process areas and NPR 7150.2a compliance matrices can motivate a software developer to consider other career fields. However with adequate definition, common-sense application, and an appropriate level of built-in flexibility, software engineering processes provide a critical framework in which to conduct a successful software development project. One problem is that current models seem to be built around an underlying assumption of "bigness", and assume that all elements of the process are applicable to all software projects regardless of size and tolerance for risk. This is best illustrated in NASA's NPR 7150.2a in which, aside from some special provisions for manned missions, the software processes are to be applied based solely on the criticality of the software to the mission, completely agnostic of the mission class itself. That is, the processes applicable to a Class A mission (high priority, very low risk tolerance, very high national significance) are precisely the same as those applicable to a Class D mission (low priority, high risk tolerance, low national significance). This paper will present real-world examples of efficient software practices, propose changes to NPR 7150.2a, taking mission class into consideration, and discuss how some of these changes are being piloted for a current Class D mission – NASA's 2011 Earth Venture Cyclone Global Navigation Satellite System (CYGNSS) mission.

8866-13, Session 3

Community satellite processing packages for real-time users

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In cooperation with the NOAA Suomi NPP/JPSS program, CIMSS/SSEC continues to expand NASA funded International MODIS/AIRS Processing Package (IMAPP) effort, and to facilitate the use of polar orbiter satellite data through the development of a newly conceived Community Satellite Processing Package (CSPP) to support the Suomi NPP and JPSS, and subsequently build up over time, to support GOES-R and other international polar orbiting and geostationary meteorological and environmental satellites for the global direct broadcast user community.

This paper highlights more than 12 years of success of IMAPP, used by ~1,500 users in 70 countries, as a foundation to the continuing development of a freely available software package to transform raw data into products and various weather and environmental applications to support Suomi NPP and subsequently the JPSS missions under the CSPP framework. Summary will be given to report on the current software release and the early operational use of Sensor Data Record (SDR) and Environmental Data Record (EDR) of VIIRS, CrIS and ATMS in National Weather Service (NWS) field offices' daily operation and many other real time users around the world for their time critical applications. research.

8866-14, Session 3

Application study of principal component based physical retrieval algorithm for hyperspectral infrared sensors

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Hyper-spectral remote sensors such as Cross-track Infrared Sounder (CrIS), Atmospheric Infrared Sounder (AIRS), and Infrared Atmospheric Sounding Interferometer (IASI) use Fourier-transform spectrometers to make high resolution thermal emission measurements, providing two orders of magnitude more spectral channels as compared to traditional sounders. Data obtained from these thousands of channels contains rich information about atmospheric temperature, moisture, and trace gas vertical profiles, cloud properties, surface emissivity spectra, and surface skin temperature. To fully utilize information content contained in these high-spectral resolution spectra and meet the real-time data processing requirement, one has to develop fast spectral analysis and inversion algorithm. An ultra-fast principal component based physical retrieval algorithm has been developed at NASA Langley research center. Core part of the algorithm is the principal component based radiative transfer model (PCRTM) which enables a single forward calculation (with Jacobian output) to be done in the milli-second time frame. And the levenberg-marquardt method based inversion algorithm can use climatological background as the first guess and retrieve the geophysical parameters simultaneously. The PCRTM can also simulate the radiative contribution from clouds, given the location of the cloud height and cloud single scattering properties. Work are under way to maximize the application potential of the PCRTM algorithm in order to generate reliable products from hyper-spectral sensor data for climate studies. The algorithm has been tested using synthetic data for various infrared sensors. This paper describes in detail about retrieval sensitivity study carried out for several hyper-spectral infrared sensors using this physical algorithm. The retrieval accuracy obtained using the algorithm for the atmospheric parameters including trace gases of interests is discussed. Its dependence on the sensor system noise and spectral resolution is illustrated by comparing the retrieval performance achieved for different sensors. Practices used to optimize the retrieval system and compensate for the possible system errors will also be addressed.

8866-16, Session 3

Automated identification of voids in three-dimensional point clouds

Katie N. Salvaggio, Carl Salvaggio, Rochester Institute of Technology (United States)

In the construction of three-dimensional (3D) point clouds from multi-view aerial imagery, voids in the point cloud often exist where multiple views of the area were not obtained during collection. A method is presented for identifying these voids. In this work, point clouds are derived from oblique aerial imagery using multi-view techniques from the photogrammetry and computer vision communities. A voxel-based approach is used to partition the 3D space and each voxel is classified as containing or not containing derived points. Using the imagery and the position of the camera, it is possible to analyze what the cameras can and cannot see, thereby making it possible to label the voxels as occupied, free, and non-classified spaces. This method has been tested on high-frame-rate oblique aerial imagery captured over Rochester, NY as well as synthetic data sets. Also presented is a unique synthetic dataset for 3D reconstruction. The data set, created with the Rochester Institute of Technology's Digital Imaging and Remote Sensing Image Generation (DIRSIG) software, provides high-fidelity radiometric data in addition to known 3D locations and surface normals for each pixel location in an image scene. This data set will be made available to the community for use in their related research.

8866-17, Session 4

Intercalibration and concatenation of climate quality infrared cloudy radiances from multiple instruments

Ali Behrangi, Hartmut H. Aumann, Jet Propulsion Lab. (United States)

A change in climate is not likely captured from any single instrument since no instrument has spanned decades of time. Therefore, to detect signals of global climate change, observations from many instruments on different platforms have to be concatenated. This requires careful consideration of multi-instrument relative biases in the spectral brightness temperatures, footprint size, and diurnal cycle of observations. A common basic assumption is that the data quality is independent of the observed scene and therefore can be determined using clear scene data. However, as will be demonstrated, this is not necessarily a valid assumption as the globe is mostly cloudy. In this study we highlight challenges in inter-calibration and concatenation of infrared radiances from multiple instruments. We illustrate this for the evaluation of data quality and to inter-calibrate different instruments for various cloudy conditions using TRMM VIRS to make correction for observational differences in the local time and foot print sizes. In this study we focus on the analysis of deep convective clouds in AIRS and IASI data. However, the approach can be applied retroactively to vintage instruments such as IRIS, AVHRR, and HIRS.

8866-19, Session 4

Scene-based Cross-comparison of SNPP-VIIRS and Aqua-MODIS over Coastal/Oceanic Waters

Nima Pahlevan, Zhongping Lee, Univ. of Massachusetts Boston (United States)

The Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (SNPP) was launched in October 2011 to continue monitoring the globe in a similar fashion as the heritage sensors, such as the MODerate resolution Imaging Spectroradiometer (MODIS). This paper applies a scene-based technique to examine in-orbit radiometric stability of VIIRS with reference to MODIS. The cross-comparison is made over bodies of waters ranging from clear oceans to coastal/inland waters. This cross-comparison allows for a comprehensive examination of the sensors' radiometric responsivity at low signal levels. The study is further extended for L2/L3 products, including remote sensing reflectance and inherent optical properties (IOPs) of waters under investigation, derived from the top-of-atmosphere (TOA) radiance (L1B). The temporal analyses give insights into the trends in the relative radiometric differences and the resulting discrepancies in the corresponding products.

8866-20, Session 4

An initial assessment of the VIIRS onboard calibration using DCC and desert referenced to the aqua-MODIS calibration

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The CERES observed EBAF 12-year TOA flux dataset are used to monitor the Earth's climate and in validating climate models. The associated cloud properties are retrieved from a fusion of MODIS and geostationary imagers. The quality of these cloud properties relies on the absolute calibration of these imagers. The geostationary imager radiances are calibrated against the Aqua-MODIS calibration reference in order to retrieve uniform cloud properties both spatially and temporally. Any calibration discontinuity or artifact may be interpreted as a climate trend. CERES record will be extended using CERES fluxes onboard NPP. CERES will need to tie the VIIRS with the Aqua-MODIS calibration in order to provide a seamless record of cloud and flux properties.

This paper will present initial assessment results for interconsistency between VIIRS and Aqua-MODIS calibration of matching visible channels. Empirically derived exoatmospheric VIIRS radiance models for deep convective clouds and desert invariant targets are used to assess the initial onboard calibration of VIIRS. The VIIRS models are based on characterizing these invariant targets with Aqua-MODIS as an absolute calibration reference. Correction for spectral band differences in the VIIRS and MODIS channels is performed using the SCIAMACHY hyperspectral data.

8866-21, Session 4

Inter-comparison between Suomi NPP VIIRS, aqua MODIS and NOAA-19 AVHRR using extended simultaneous nadir overpass in the low latitudes for consistent radiometric calibration

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Suomi NPP VIIRS has been undergoing extensive calibration/validation efforts in order to produce high quality weather and climate related satellite data products. VIIRS absolute radiometric accuracy and consistency can be achieved by inter-comparing its measurements with other well calibrated instruments such as AQUA MODIS. This study uses simultaneous nadir overpass extended to low latitudes (SNO-x) for comparing VIIRS with MODIS at more uniform and stable sites such as deserts. VIIRS moderate bands compared with matching MODIS bands at North African desert reveals that the radiometric bias at desert for channels M-1 through M-8 is less than 2% after accounting for spectral differences. VIIRS is a follow on mission for MODIS and AVHRR. In an effort to establish radiometric consistency of VIIRS with multi-decadal global earth observations from AVHRR, this study uses SNO-x approach to inter-compare VNIR channels of NOAA-19 AVHRR measurements with VIIRS at desert. The inter-comparisons are performed at nadir and at off-nadir angles and the impact due to spectral differences are quantified using MODTRAN and hyperspectral measurements from EO-1 Hyperion.

8866-22, Session 4

Inter-comparison of METOP-A and METOP-B AVHRR and on-orbit calibration update

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Meteorological Operational (METOP)-B spacecraft was launched on September 17, 2012, and the Advanced Very High Resolution Radiometer (AVHRR) visible and near-infrared channels were activated shortly after the launch. After on-orbit verification of the instrument performance, an important task is to update the visible and near-infrared channel calibration coefficients. Due to the lack of on-board calibrator, the post-launch calibration can only be carried out vicariously, and Libyan Desert has been used as reference since 1995.

The seasonal variation of Libyan Desert reflectance has been considered in the calibration, and, for early time of the post-launch, the seasonal variations are derived from previous AVHRR measurements. A new method has been developed using the MetOp-A and MetOp-B inter-comparison with consideration of the BRDF effect, and applied to the calibration update. Since these two satellites are in the same orbit with half orbit time (~50min) apart, it may be possible to use the inter-comparison of the AVHRR measurement on Libyan Desert between the instruments on board of them for MetOp-B calibration. However, the solar zenith angle and sensor zenith angle are not the same for the collocated measurements, and the Bidirectional Reflectance Distribution Function (BRDF) affects the comparison. The zenith angle dependent measurements have been modeled and the comparison of the reflectance with the same solar zenith angle and sensor zenith angle has been derived. The calibrations from these two methods are consistent and the updates are ready for the delivery. This work is also useful to investigate BRDF effect on the inter-comparison.

8866-23, Session 5

Ground viewing radiometer characterization, implementation and calibration applications: a summary after two years of field deployment

Nikolaus J. Anderson, Jeffrey Czapla-Myers, College of Optical Sciences, The Univ. of Arizona (United States)

In 2011, three improved ground-viewing radiometers (GVRs) were built and deployed to support the Radiometric Calibration Test Site (RadCaTS) developed by the Remote Sensing Group (RSG) at the University of Arizona. The GVRs are filter-based radiometers with eight spectral channels covering a wavelength range of 400-1550 nm. They are automated, field-deployable instruments capable of long-term, standalone operation. The radiometers are temperature-controlled and designed for greater stability and lower noise.

This work describes the deployment period of these radiometers with particular attention paid to the in-field performance, reliability, and results from these instruments. Using other RadCaTS inputs including meterological station data and Aerosol Robotic Network (AERONET) Cimel sun photometer data, select vicarious calibration results are presented. With these results, an assessment of the calibration applications of the RadCaTS during new GVR deployment is discussed. In addition, GVR calibration and characterization results, including solar radiation based calibration (SRBC), are presented as another means of assessing the performance of the radiometers over deployment periods.

8866-26, Session 5

Monitoring NPP VIIRS On-Orbit Radiometric Performance from TOA Reflectance Time Series

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The recently launched (October 28, 2011) Suomi NPP (National Polar-orbiting Partnership) satellite (http://npp.gsfc.nasa.gov/viirs.html) has been operating nominally to daily collect global data. The Visible Infrared Imaging Radiometer Suite (VIIRS) is a key NPP sensor, similar to the heritage sensor MODIS. VIIRS has on-board calibration components including a solar diffuser (SD) and a solar diffuser stability monitor (SDSM) for the reflective solar bands (RSB), a V-groove blackbody for the thermal emissive bands (TEB), and a space view (SV) port for background subtraction. This study examines VIIRS RSB calibration stability and performance using observed top-of-atmosphere (TOA) reflectance time series collected from two approaches. The first is from comparison with a well-calibrated Aqua MODIS and the second is from overpasses over the widely used Liby-4 desert site. The VIIRS and MODIS comparison data is obtained from simultaneous nadir overpasses (SNO) for their spectrally matched bands. The impact due to the band spectral differences between the two instruments is corrected based on MODTRAN5 simulations. The reflectance trends over the Libya-4 site are extracted from 16-day repeatable orbits so each data point has the same viewing geometry relative to the site. Results of this study provide useful information on NPP VIIRS post-launch calibration assessment and preliminary analysis of its calibration stability and consistency for the first 1.5 years.

8866-27, Session 5

Vicarious calibration of Suomi NPP VIIRS day-night band

Joel McCorkel, NASA Goddard Space Flight Ctr. (United States)

The Suomi National Polar-orbiting Partership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) is a moderate resolution radiometer that acquires a full earth image every day in 22 spectral channels in the visible to thermal infrared. One of these channels is panchromatic across the solar reflective and called the Day-Night Band (DNB). The DNB has three gain regions and radiometric resolution to provide sensitivity in over seven decades required for imaging the range of dimly illuminated earth-night scenes to typical solar-illuminated scenes. Performance of the DNB since the launch of NPP in October 2011 is excellent having shown capability of detecting the illumination from airglow and starlight. Significant effort went into understanding and characterizing the radiometric calibration of all VIIRS channels pre- and post-launch. This paper provides vicarious calibration results for the DNB to complement these efforts with an independent approach. This work will use imagery of desert sites gathered with sensors with well-known radiometric calibration in combination with lunar and solar databases to provide an absolute radiometric characterization for the VIIRS DNB.

8866-28, Session 5

Early ground-based vicarious calibration results for Landsat 8 OLI

Jeffrey Czapla-Myers, Nikolaus J. Anderson, Stuart F. Biggar, College of Optical Sciences, The Univ. of Arizona (United States)

The Operational Land Imager (OLI) is one of two instruments onboard the Landsat 8 platform, which was launched in February 2013 from Vandenberg Air Force Base in California. The multispectral bands of OLI retain the 30-m spatial resolution of Landsat 5 TM and Landsat 7 ETM+, but improvements to the system include 12-bit radiometric resolution, and nine bands in the VNIR and SWIR spectral regions. The earlier TM and ETM+ sensors use a whiskbroom configuration, while OLI uses a pushbroom configuration, which allows it to have a much larger signal-to-noise ratio than previous Landsat instruments. This also creates challenges in radiometric calibration due to the large number of detectors on the focal plane.

Long-term data continuity is a crucial component of the 40-year Landsat series of satellites, and ground-based vicarious calibration has played an important role in ensuring that these sensors remain on the same radiometric scale. This work presents the early ground-based in-flight radiometric calibration of OLI, which was determined using the traditional and well-understood reflectance-based approach, as well as the Radiometric Calibration Test Site (RadCaTS), which is an automated suite of instruments located in central Nevada.

8866-29, Session 6

Calibration status of the atmospheric infrared sounder after eleven years of operation

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The Atmospheric Infrared Sounder (AIRS) is a grating array infrared hyperspectral sounder with 2378 channels from 3.75 to 15.4 microns with spectral resolution 1200 to 1400 depending on the channel. AIRS was designed as an aid to weather prediction and for atmospheric process studies. It produces profiles of atmospheric temperature and water vapor. Because of its spectral coverage and spectral resolution it is sensitive to a number of trace atmospheric constituents including CO_2, CO, SO_2, O_3, and CH_4. The AIRS sensitivity, stability, and long life have led to its use in climate process studies and climate model validation, both of which place far more stringent requirements on calibration than weather forecasting does. This paper describes results from several special calibration sequences, originally developed for pre-launch testing, that have been used in the last year to monitor the AIRS calibration accuracy, including the handling of instrument polarization, space view response, and channel health.

8866-30, Session 6

Lessons learned from the AIRS pre-flight radiometric calibration

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NASA's Atmospheric Infrared Sounder (AIRS) is a hyperspectral infrared instrument that covers the infrared spectrum from 3.7-15.4 um with 2378 channels and flies on the EOS Aqua spacecraft. AIRS has demonstrated exceptional radiometric accuracy to better than 0.1K for module averages at scene temperatures of 265K (Pagano, SPIE 2008). Several channels and band edges do not perform as well, primarily due to vignetting within the system or polarization effects. While the performance of AIRS is exceptional, small errors in the calibration result particularly at cold scene temperatures from errors in the knowledge of scan mirror polarization. Two methods are explored to improve the calibration of AIRS in the infrared that are applicable to other instruments. The first method uses the intercept of the fit to the linearity test to determine the polarization terms, while the second inverts the calibration equation to improve handling of second order effects of polarization in the calibration. These methods could be applied to other infrared instruments with mirror polarization effects.

8866-31, Session 6

Space view issues for hyperspectral sounders

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The expectation from hyperspectral sounders is absolute calibration accuracy at the 50 mK level and stability at the < 5 mK/yr level. The AIRS, CrIS, and IASI hyperspectral sounders currently in orbit have been shown to agree well over most of their brightness temperature range. Some larger discrepancies are seen, however, at the coldest scene temperatures, such as those seen in Antarctic winter and deep convective clouds. A key contributor to the calibrated scene radiance uncertainty for cold scenes is the assumption that the effective radiance of the cold space view pertains to the scene views. The spaceview signal is actually the sum of external sources, the instrument thermal emission, the scan mirror, and associated external baffles, all at the spacecraft ambient temperature of about 270 K. Any difference in any of these contributions between spaceviews and scene views will impact the absolute calibration accuracy, especially for cold scenes. Any change over time in these will show up as an apparent trend in calibrated radiances. We use AIRS data to investigate the validity of the spaceview assumption in view of the 50 mK accuracy and 5 mK/yr trend expectations.

8866-32, Session 6

Results from CrIS/ATMS using the AIRS Science Team retrieval methodology

Joel Susskind, NASA Goddard Space Flight Ctr. (United States)

The NPP mission was launched in October 2011 as part of a sequence of Low Earth Orbiting satellite missions under the "Joint Polar Satellite

System" (JPSS). The future JPSS missions, J1 and J2, are currently scheduled for November 2016 and November 2021 launches. The J1 mission will be very similar to NPP, using the same spacecraft and instrument complement. NPP carries CrIS and ATMS, which are advanced infra-red and microwave atmospheric sounders that were designed as follow-ons to the AIRS and AMSU instruments flying on EOS Aqua. We have been conducting research to optimize products derived from CrIS/ATMS observations using a scientific approach analogous to that used by the AIRS Science Team. Results will be shown comparing the quality and spatial coverage of GSFC CrIS/ATMS sounding products to those of NOAA-derived CrIS/ATMS products, as well as those of AIRS/AMSU products derived using the currently operational AIRS Science Team Version-6 retrieval algorithm. The main objective of this work, from the NASA perspective, is to assess whether CrIS/ATMS is an adequate replacement for AIRS/AMSU from the perspective of the generation of long term Climate Data Records, or if improved instruments should be developed for flight on J2.

8866-33, Session 6

Detection of extremes with AIRS, IASI, and CRIS

Hartmut H. Aumann, Jet Propulsion Lab. (United States)

Climate change is expected to be detected first as changes in extreme values rather than in mean values. Since AIRS, IASI and CRIS are producing data at the same time, we can determine if there are significant differences in extreme values. For the analysis of extreme values we analyze the Probability Density Functions (PDF) of the brightness temperatures in the 900 cm-1 atmospheric window channels created from about 2 million spectra collected between April and December 2012 in the tropical oceans. The mean brightness temperatures from the three instruments, 283.6K, agree within 10 mK. This excellent agreement confirms conclusions from tests under more restricted conditions, that on average the calibration of the three instruments is excellent. However, IASI and CRIS both find significantly more extremely hot cases than AIRS. For example the 99.9% of the PDF for IASI is 1.2 K warmer than for AIRS, for CRIS it is 2.4K warmer than for AIRS. Experiments with data quality filters available from the CRIS L1b imaginary component of the radiances confirm that this is an artifact of the CRIS calibration. Similar diagnostic information is not available from the IASI L1c data. Future releases of re-processed CRIS and IASI data may mitigate these effects. As is, we conclude that significant difference in extreme values can be found in the three instruments. If the data from AIRS, IASI and CRIS were interpreted as samples from three different instruments representative of future time periods separated by decades, the observed differences in the extreme value could be misinterpreted as evidence of changes in frequency of extreme cases due to climate change.

8866-34, Session 7

MERIS calibrations: 10 years

Steven Delwart, European Space Agency (Italy); Ludovic Bourg, ACRI-ST (France)

The calibration results from the MEdium Resolution Imaging Spectrometer (MERIS) on board the ENVISAT satellite over its ten years of operation of will be presented.

These will include radiometric and spectral calibration results using the on-board diffusers as well as radiometric validation results from a number of vicarious calibration methods.

8866-35, Session 7

Pleiades-HR 1A&1B image quality commissioning: innovative radiometric calibration methods and results

Vincent Martin, Gwendoline Blanchet, Philippe Kubik, Sophie Lacherade, Christophe Latry, Laurent Lebegue, Florie Lenoir, Florence Porez-Nadal, Ctr. National d'Études Spatiales (France)

PLEIADES is an earth observing system conducted by the French National Space Agency, CNES. It consists of two satellites launched on December 2011 (PHR-1A) and December 2012 (PHR-1B), both designed to provide to civilian and defence users optical push-broom imagery on five spectral bands, with ground sample distance up to 70 cm. During in-flight image quality commissioning, radiometric activities included inter-detector normalization coefficients computation, refocusing operations, MTF assessment and estimation of signal to noise ratios. This paper presents in-flight results for both satellites. It focuses on several innovative methods that were implemented, taking advantage of the satellite platform great agility. These methods are based on processing images obtained through dedicated exotic guidance. In particular, slow-motion steering enables an efficient estimation of the instrumental noise model, since during acquisition each detector has been viewing a stable ground target along different time samples. Conversely, rotated retina guidance is used to guarantee that all different elementary detectors have successively viewed the same set of landscape samples during acquisition. Non-uniformity of detector sensitivities can then be characterized, and on-board coefficients used prior to compression can be calibrated in order to prevent vertical striping effects on operational images. Defocus control and Point Spread Function estimation can be easily obtained through processing acquisitions of stars associated to various spectral characteristics, for different adjustments of the refocusing system. All these methods allow an accurate estimation of radiometric performance on the whole range of specified spectral radiances, while drastically reducing the number of required acquisitions on natural targets.

8866-36, Session 7

Pleiades satellites image quality commissioning

Laurent Lebegue, Daniel Greslou, Gwendoline Blanchet, Christophe Latry, Vincent Martin, Francoise de Lussy, Sébastien Fourest, Ctr. National d'Études Spatiales (France); Sophie Lacherade, Ctr National d'Études Spatiales (France); Jean Marc Delvit, Cecile Dechoz, Virginie Amberg, Florence Porez-Nadal, Florie Lenoir, Philippe Kubik, Ctr. National d'Études Spatiales (France)

PLEIADES is the highest resolution civilian earth observing system ever developed in Europe. This imagery program is conducted by the French National Space Agency, CNES. The first satellite has been launched December 17th 2011, and the second one December 2nd 2012. Each satellite is designed to provide optical images to civilian and defense users. Images are simultaneously acquired in Panchromatic (PA) and multi-spectral (XS) mode, which allows, in nadir acquisition condition, to deliver 20 km wide, false or natural colored scenes with a 70 cm ground sampling distance after PA+XS fusion. Coverage is almost world-wide with a revisit interval of 24 h for the 2 satellites.

The assessment of the image quality and the calibration operation has been performed by CNES Image Quality team during the 6 month commissioning phases that followed each satellite launch. These activities cover many topics such as absolute calibration, the normalization coefficients computation, the refocusing operations, the MTF assessment, the estimation of signal to noise ratio, the geometric model calibration, the assessment of localization accuracy, multi-spectral overlapping, static and dynamic stability, planimetric and altimetric accuracy. These operations required specific control of the payload and dedicated guidance of the satellite platform. The new capabilities offered

by PLEIADES satellites agility allowed to imagine new methods of image calibration and performances assessment.

Starting from an overview of the satellite and instrument characteristics, this paper present all the calibration operations that were conducted during the commissioning phases and also give the main results for every image quality performance.

8866-37, Session 7

Pleiades-HR 1A&1B image quality commissioning: innovative geometric calibration methods and results

Daniel Greslou, Francoise de Lussy, Virginie Amberg, Cecile Dechoz, Jean Marc Delvit, Laurent Lebegue, Ctr. National d'Études Spatiales (France)

PLEIADES is an earth observing system conducted by the French National Space Agency, CNES. It consists of two satellites launched on December 2011 (PHR-1A) and December 2012 (PHR-1B). The system has been designed to provide to civilian and defense users 20 km wide Earth images , on five spectral bands, with ground sample distance up to 70 cm. This constellation allows an almost world-wide coverage with a revisit interval of less than 24 h.

The assessment of the image quality and the calibration operation of the two satellites have been performed by CNES Image Quality team during the called commissioning phase that follows the satellite launch.

The geometric commissioning activities consist in asses and improve the geometric quality of the images in order to meet very demanding specifications as localization accuracy, local coherence, dynamic stability, lengths alteration… This goal has been achieved in particular through the implementation of new methods of calibration and performance assessment. Some of these methods are based on the exploitation of very specific satellite acquisitions that have been achieved thanks to the amazing agility of the Pleiades satellite. Thus, many stars acquisitions and very slow earth pictures have been processed to characterize dynamic phenomena. Similarly, "along-cross track" pairs have been exploited to improve the accuracy of the focal plane description.

This paper deals with these new methods; it describes their accuracy and their operational interest. It concludes with an overview of the main geometric results and performances reached on each satellite.

8866-38, Session 7

In-flight attitude perturbances estimation: application to Pleiades-HR satellites

Virginie Amberg, Cecile Dechoz, Ctr. National d'Études Spatiales (France); Laurent Bernard, Magellium (France); Laurent Lebegue, Francoise de Lussy, Daniel Greslou, Ctr. National d'Études Spatiales (France)

This paper deals with the problem of retrieving attitude perturbances in the framework of in-flight high resolution optical satellites. The objective is to estimate high frequency perturbances, ranging above the gyros cutoff frequency, that could corrupt the image. During the in-flight commissioning period of PLEIADES-HR satellite, this analysis was necessary to choose the optimal rotation speed of gyroscopic actuators in the mean of geometrical image quality. In this context, two methods have been tested and compared. The first one uses the high agility capacity of PLEIADES-HR satellites to acquire stars in an inertial steering mode. The resulting image permits to access directly to the attitude perturbance. The second method exploits the design of the PLEIADES-HR instrument: multi-spectral bands are shifted in the telescope focal plane in the velocity direction. Therefore, acquisitions are not simultaneous in the different spectral bands which means that, for a same ground point, images are not affected by the same attitude perturbance. Thus there are misregistrations between images that can be measured by correlation techniques in order to deduce the platform attitude during the acquisition. Finally, for both methods, perturbation frequencies are estimated thanks to spectral analysis and results are compared.

The first method allows to estimate the attitude perturbances with a high precision in the roll direction. Whereas the second method is less accurate because of correlation process but allows to access to attitude perturbances in both roll and pitch directions. In conclusion, the two methods are complementary.

8866-39, Session 7

METOP-B, the second satellite of the EUMETSAT polar system, in orbit

K. Dieter Klaes, Francois Montagner, European Organisation for the Exploitation of Meteorological Satellites (Germany); Carole Larigauderie, Centre National d'Etudes Spatiales (France)

The EUMETSAT Polar System is EUMETSAT's contribution to the Global Observing System in the polar sun-synchronous orbit and serves, in the frame of the Initial Joint Polar System (IJPS) with the United States, the mid-morning orbit. The space segment is composed of the Metop satellites, of which Metop-A is in orbit since 2006, providing a wealth of Earth Observation data, amongst them data for Atmospheric Sounding, cloud and surface monitoring, ocean observation, including ocean winds, atmospheric composition monitoring. The launch of Metop-B on the 17 September 2012 into the same mid-morning orbit (9:30 LST equator crossing time, descending node, phased 48 min. apart from Metop-A) at 820 km assures the continuity of the system. A third Metop satellite (Metop-C), scheduled for launch early 2018, will assure a mission duration of at least 15 years. This paper will discuss the status of the EUMETSAT Polar System (EPS) and in particular present the results from Metop-B commissioning and the actual status of products. Metop-B will be out of its commissioning at the time of the conference and is planned provide its service together with Metop-A, which is healthy and is planned continue its successful service.

8866-40, Session 8

Characterization of a radiometric monitoring system for NASA code 618's SIRCUS-G

Leibo Ding, John W. Cooper, Aboubakar Traore, Gilbert R. Smith, Sigma Space Corp. (United States); James Butler, NASA Goddard Space Flight Ctr. (United States)

A tunable, intensity-stabilized, quasi-continuous wave (CW) laser system, patterned after the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) system at the National Institute of Standards and technology (NIST), has been installed and tested in the NASA Goddard Space Flight Center (GSFC) Code 618 Biospheric Sciences Laboratory's Calibration Facility. This system is referred to as SIRCUS-G (SIRCUS-Goddard). The tunable output of the laser system is fiber fed to a 76.2 cm diameter integrating sphere lined with Spectralon. The uniform radiance light emitted from the integrating sphere is used in system-level radiometric responsivity characterizations and wavelength calibrations of remote sensing instruments. The primary radiance reference standard in the responsivity characterizations is a three-element trap detector calibrated by NIST. This detector is located at the exit port of the Spectralon coated integrating sphere. In addition, a set of detectors are mounted on integrating sphere wall ports to monitor source radiance and to provide real-time sphere radiance data during the calibrations of remote sensing instruments. These monitor detectors provide spectral coverage from 300nm to near 2500nm. This paper presents the results of our characterization of the performance of these monitor detectors. Results are presented and discussed on monitor detector short- and long-term system stability, noise level, and total measurement uncertainty.

8866-41, Session 8

The NIST robotic optical scatter instrument (ROSI) and its application to BRDF measurements of diffuse reflectance standards for remote sensing

Heather J. Patrick, National Institute of Standards and Technology (United States); Clarence J. Zarobila, Jung Research and Development Corp. (United States) and National Institute of Standards and Technology (United States); Thomas A. Germer, National Institute of Standards and Technology (United States)

The Sensor Science Division of the National Institute of Standards and Technology (NIST) is in the process of expanding its facilities for reference measurements of diffuse and specular reflectance of materials, including measurements of bidirectional reflectance distribution factor (BRDF) of diffuse reflectance standards that provide traceability for diffuser plaques used as onboard calibration standards in remote sensing. Currently, BRDF of spectrally neutral diffuse samples is measured in the NIST STARR facility. STARR provides wavelength-resolved BRDF measurements from the ultraviolet to the short-wave infrared (approximately 250 nm – 2500 nm), for a limited range of in-plane incident and scattering angle geometries. However, remote sensing systems often use diffusers in out-of-plane configurations, where the viewing angle is rotated from the incident plane formed by the light source incident angle and the normal to the sample. In order to be able to replicate these out-of-plane measurement geometries, NIST recently took delivery of a robotic-arm based goniometer system, nicknamed “ROSI”, that will enable BRDF measurements to be made at nearly any combination of incident and scattering angles.

In this presentation, we will describe the new robotic goniometer and its use for in-plane and out-of-plane reflectance measurements. We will discuss techniques for verifying and establishing the accuracy of out-of-plane angular motions, methods to compensate for sample thickness and wedge, and the projected range of incident and scattering angles that will be accessible to ROSI. We also plan to show measurements of in-plane and out-of-plane BRDF for nominally Lambertian diffuse reflectors.

8866-42, Session 8

Potential use of two ultraviolent bands sensor on the HY-1C/D satellites

Zhihua Mao, The Second Institute of Oceanography, SOA (China)

China has launched two ocean color satellites and plan to launch the next two satellites HY-1C/D in 2015. HY-1C/D are the two same satellites running together with HY-1C at 10:30 AM and HY-1D at 1:30 PM, to improve the frequency of data coverage. Two sensors of the China Ocean Color and Temperature Sensor (COCTS) and Coastal Zone Imager (CZI) will still be installed on HY-1C/D. A new sensor with two ultraviolent (UV) bands for ocean environmental monitoring will also be installed on the satellites. One important potential use of the UV bands is for the development of a new algorithm of the atmospheric correction for turbid coastal waters. As well known, the standard atmospheric correction method based on the two near-infrared (NIR) bands fails for the turbid waters because the reflectance at NIR bands is much larger than zeros. We found that the reflectance at UV bands is close to zeros from in situ measurements. Therefore, the reflectance at UV bands can be used for a new atmospheric correction algorithm. The new algorithm is validated by simulation data, MODIS and GOCI data. The results show that the accuracy of the atmospheric correction has been improved for turbid waters. This algorithm is a potential method for the atmospheric correction of HY-1C/D data.

8866-43, Session 8

A new airborne Ka-band double-antenna microwave radiometer for cloud liquid water content measurement

Jian Sun, Jilin Univ. (China) and Northeast Institute of Geography and Agroecology (China); Kai Zhao, Tao Jiang, Northeast Institute of Geography and Agroecology (China)

A new type upward-looking airborne double-antenna microwave radiometer (ADAMR) system intended for detecting atmospheric cloud liquid water content (LWC) is developed in this paper. The frequency of this radiometer is 31.65 GHz. For the antenna elevation angle, one is and the other is . In order to detect the signals with low effective noise temperature (<10K) from the LWC, the noise coupling technique is used. Through injecting constant equal noise signal into the two antenna ports respectively, the technique can elevate the small input noise signal power to the detectable range of the square-law detector and thus realize the weak signal detection. Moreover, in order to eliminate the impacts of the system gain fluctuations and obtain a higher sensitivity, an auto-gain compensation method based on the analog-to-digital converter, microcontroller and host computer software techniques is also proposed. Compared with the traditional radiometers, the radiometer topology is greatly simplified and the gain fluctuations can be readily real-time compensated using the compensation method. The laboratory test results show that radiometric sensitivity is better than 0.2 K for 300ms integration time and the instrument is conforming to specifications. Finally, the flight observation experiment results are presented to prove that the designed instrument is able to detect small changes of noise signal in a wide effective range of noise temperature (10-350K) and is a powerful tool for LWC measurement.

8866-101, PL Session

The geostationary remote infrared pollution sounder: measurement of the carbon gases from space

Mark Schoeberl, Hal J. Bloom, Ryan Spackman, Science and Technology Corp. (United States); Chad S. Fish, Space Dynamics Lab., Utah State Univ. Research Foundation (United States); Martin J. McHugh, Larry L. Gordley, GATS, Inc. (United States)

We describe an instrument for the measurement of carbon gases and its earth remote sensing capabilities from geostationary orbit. Carbon gases CO, CH4, and CO2 are key components of climate change and air quality. CO, with the shortest lifetime, is produced by fires and industrial processes. It plays a role in ozone formation and is a surrogate for black carbon aerosols and smoke. CH4 is a powerful greenhouse gas produced by biogenic process, leaks from pipelines and extraction complexes, and fires. CH4 sources and sinks are highly uncertain. CO2 is also a powerful greenhouse gas, but despite years of study, its sinks are still uncertain. Using the combination of these gases, we can fingerprint sources of pollution. Our instrument concept, the Geostationary Remote Infrared Pollution Sounder (GRIPS), will provide rapid temporal and high spatial resolution measurements of these carbon gases from space. The instrument is designed to quantify the concentration, sources, and fluxes of these gases over the extra-polar regions from geostationary orbit. One advantage of the geostationary orbit is that more measurements in cloud-free regions can be made in a few days than can be made in several weeks of low earth orbit measurements. A second advantage is that we can resolve the diurnal component of the gas concentration. This allows better tracking of plumes and identification of sources. Unlike the thermal infrared sensors on AIRS, MOPITT, and IASI, GRIPS uses the near- and short-wave infrared to make measurements in the boundary layer, where the sources and sinks are active.

8866-45, Session 9

Critical CCD and CMOS image sensor technology development and ESA space qualification approach in support ESA Earth observation and science missions

Mustapha Zahir, European Space Research and Technology Ctr. (Netherlands)

Image sensors such as CCDs and CMOS detectors are at the core of most ESA space missions, and in many cases form the basis for the only or the main instrument payload. Although high performance scientific applications are based on CCDs, CMOS image sensors are gaining popularity as a replacement for CCDs, as the technology improves in QE and noise performances. Image sensors, both CCD and CMOS, development are an important strategic elements of the ESA Earth Observation as well as science Programmes, as they are enabling technologies for many space missions.

In this paper, we will provide an overview of ESA development road map for Image sensors technology. We will address, current and future development and qualification programs. ESA and industrial partners are undertaking many development programs to fulfil earth observation and science missions requirements, such as GAIA, Euclid, MTG, GMES.

The paper will also provide ESA approach in space evaluation and qualification of image sensors, based on the international ESCC standards. Currently the ESCC 9020 is the main generic specification addressing CCDs and CMOS image sensors, with plans for developing similar standard for IR detector. Standards for Test methods for CCDs has already been developed while similar standards for CMOS and IR detectors are being developed. The difference between project qualification and ESCC qualification will be explained and lessons learned will be shared.

8866-46, Session 9

A remote sensing optical design for the OpenOrbiter CubeSat

Nicholas Long, Rachael Roberts, Dillon Hasselmann, Atif Mohammad, Jeremy Straub, Joshua Berk, Noah Root, The Univ. of North Dakota (United States)

OpenOrbiter is a 1-U form-factor CubeSat-class spacecraft with a remote sensing payload being developed at the University of North Dakota. It is designed to validate the performance of the Open Prototype for Educational NanoSats (OPEN) framework, which seeks to reduce the cost of small spacecraft development.

This paper presents the OpenOrbiter optical system and evaluates it for use for Earth remote sensing applications. System limitations include the small optical aperture size, the movement of the satellite with respect the ground and atmospheric blurring. The spacecraft size dictates that the optical system fit within a 5 cm x 5 cm x 5 cm compartment within the overall CubeSat size of 10 cm x 10 cm x 11 cm.

The small aperture size means that it will be possible to obtain a maximum spatial resolution of about 150 m, based on a prospective 300 km low-Earth orbit. The satellite's orbital velocity of approximately 7.5 to 8 km/s will cause motion blur during image capture. Light scattering from the atmosphere will further degrade image quality. A constant blurring effect is presumed, for the purposes of resolution specification, based on the assumption that the camera is pointing at nadir. Optical defects will further limit the resolution of the image. Onboard post processing includes mosaicking and super resolution. Thumbnail versions of images are sent to controllers for selection of what images to download over the limited communications bandwidth available. The possibility of various remote-sensing applications is considered, based on all of the aforementioned optical limitations.

8866-47, Session 9

MTG FCI optical design and performances

Julien Ouaknine, Sophie Gode, Bruno Napierala, Thierry Viard, Thales Alenia Space (France); Ute Foerster, Sebastian Fray, Patrick Peacoke, Michael Hartl, Kayser-Threde GmbH (Germany); Pascal Hallibert, European Space Research and Technology Ctr. (Netherlands); Yannig Durand, European Space Agency (Netherlands)

Meteosat Third Generation is the next ESA Program of Earth Observation Satellites dedicated to Weather Forecast from the Geostationary orbit, using a 3 axis stabilized platform. The main payload is called the Flexible Combined Imager, currently under development by Thales Alenia Space.

This instrument will provide full images of the Earth every 10 minutes in 16 spectral channels between 0.44 and 13.3 µm, with a ground resolution ranging from 0.5 km to 2 km.

The FCI is composed of a TMA telescope developed by Kayser-Threde, which includes a Scan mirror enabling to image the Earth, as well as a calibration mechanism with an embedded black body dedicated to accurate in-flight radiometric calibration. The intermediate image produced by the telescope is then split into several spectral groups by a spectral separation assembly with dichroïc beamsplitters. The output beams are collimated to ease the instrument integration, and reach the cold optics which focalize the optical beams onto the detectors. The cold optics and IR detectors are accurately positioned inside a common cryostat to improve coregistration between spectral channels. Spectral filters are integrated on top of the detectors in order to achieve the required spectral selection.

This article will describe the optical design and the main optical performances of the FCI : a good image quality, a very high line-of-sight stability, and an efficient rejection of stray-light thanks to implementation of dedicated baffles and a stringent control of contamination.

The FCI currently under development, is expected to exhibit a significant improvement of performances with respect to Meteosat Second Generation satellites.

8866-48, Session 10

Landsat data continuity mission (LDCM): six months on-orbit

Brian L. Markham, James R. Irons, NASA Goddard Space Flight Ctr. (United States)

The Landsat Data Continuity Mission (LDCM) was launched on February 11, 2013. LDCM is a joint mission between NASA and the United States Geological Survey (USGS). About 3 months after launch the LDCM lead role will transition to the USGS and the mission will be renamed Landsat-8. This presentation will give an update on the mission as of the date of the conference. Other papers have been submitted that will provide more details about the two instruments on LDCM: The Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS).

8866-49, Session 10

Early radiometric performance assessment of the Landsat-8 operational land imager (OLI)

Julia A. Barsi, Brian L. Markham, NASA Goddard Space Flight Ctr. (United States)

Landsat-8, the latest in the Landsat series of satellites, was launched on February 11, 2013 and carries on board the Operational Land Imager (OLI) as one of its payloads. The satellite's mission is to continue the long history of operational land imaging of the Landsat program. The OLI follows the highly successful Landsat-5 and Landsat-7 in continuing to populate an archive of earth images that dates back to 1972.

The OLI has significant changes from the Landsat Thematic Mapper instruments: it is the first pushbroom instrument; it includes a cirrus band and an ultra-blue band; and the thermal bands are in a separate instrument.

On-board radiometric calibration devices include a full-aperture shutter for a measure of the dark levels, a solar panel for calibration against the sun, and multiple sets of lamps for short-term stability monitoring. The satellite will regularly perform maneuvers to image the moon for lunar calibrations and turn sideways to in order that all detectors image the same point on the ground. Additionally, the OLI will make use of vicarious calibration campaigns by University of Arizona and South Dakota State University, as well as monitoring large desert targets in the Sahara for long-term stability.

This paper will cover the early results of the calibration and characterization that have been performed since launch.

8866-50, Session 10

Preliminary on-orbit performance of the thermal infrared sensor (TIRS) on board Landsat 8

Matthew Montanaro, Sigma Space Corp. (United States); Dennis Reuter, Brian L. Markham, Allen Lunsford, NASA Goddard Space Flight Ctr. (United States); Zelalem Tesfaye, SGT, Inc. (United States) and NASA Goddard Space Flight Ctr. (United States); Brian Wenny, Sigma Space Corp. (United States); Kurtis Thome, Ramsey Smith, NASA Goddard Space Flight Ctr. (United States)

The Thermal Infrared Sensor (TIRS) on board Landsat 8 continues thermal band measurements of the Earth for the Landsat program. TIRS improves on previous Landsat designs by making use of a pushbroom sensor layout to collect data from the Earth in two spectral channels. To ensure proper radiometric integrity, TIRS was calibrated to a NIST absolute radiometric standard during pre-flight testing and characterization. Calibration methods and algorithms were developed to translate the raw signal from the instrument into an accurate at-aperture spectral radiance. The TIRS instrument also has the ability to view an on-board variable-temperature blackbody and a deep space view port for calibration purposes. The calibration routines were also used to transfer the NIST radiometric knowledge to the TIRS on-board blackbody calibrator.

After TIRS was successfully activated on-orbit, checks were performed on the instrument data to determine its image quality. These checkouts included assessment of the on-board blackbody and deep space views as well as normal Earth scene collects and vicarious calibration sites. The TIRS radiometric performance will be regularly monitored using these methods and updates to the calibration algorithms are implemented as necessary to maintain the radiometric accuracy of the data product. An overview of the radiometric calibration process developed pre-flight is given here along with a summary of early on-orbit checkout activities. In addition, a comparison of the pre-flight and early on-orbit performance is discussed.

8866-51, Session 10

Ghosting and stray-light performance assessment of the Landsat data continuity mission's (LDCM) operational land imager (OLI)

Philip W. Dabney, Raviv Levy, Brian L. Markham, Eugene Waluschka, Lawrence Ong, NASA Goddard Space Flight Ctr. (United States); Frank Grochocki, Michael G. Dittman, Ball Aerospace & Technologies Corp. (United States); Jeffrey A. Pedelty, NASA Goddard Space Flight Ctr. (United States)

The newly launched Operational Land Imager (OLI) aboard the LDCM satellite has stringent requirements to control t ghosting and diffuse stray-light in the reflective bands in order to preserve the radiometric accuracy of high contrast images.. The LDCM project science team working with the instrument teams wrote the requirements such that they were image based, inclusive of all effects that appear to be ghosts or stray-light, and consequently more directly testable. The OLI Instrument Developer, Ball Aerospace & Technologies Corporation, working closely with experts from aerospace, academia, and the NASA/USGS LDCM project were able to identify and mitigate the various contributors to ghosting and stray-light, resulting in an outstanding image performance for a wide field-of-view push-broom imaging sensor.

We will describe the ghosting and stray-light requirements and some of the contributing effects such as the leaky pixels that were seen on the EO-1/ALI. we will also highlight some of the technical challenges encountered and the solution resulting in the substantial reduction of ghosting and straylight which were verified by ground test. We will compare these ground measurements and analytic predictions with Lunar scan data to potentially resolve the question of whether the source of some of the performance outliers was the instrument or the test equipment.

Finally, we will discuss the impacts the pre-launch and image estimated values of each will have on the LDCM radiometric accuracy.

8866-52, Session 10

Intercalibration of Landsat 8 using scaled measurements

Joel McCorkel, Kurt Thome, NASA Goddard Space Flight Ctr. (United States)

The launch of Landsat 8 on 11 February 2012 continues a chain of land surface imaging from space started in 1972 with the launch of Landsat 1. Landsat 8 hosts Operational Land Imager (OLI) with spectral channels in the visible to shortwave infrared and Thermal Infrared Sensor (TIRS) with spectral channels in the thermal infrared. Many of the spectral channels in the OLI and TIRS design were also present in previous Landsat sensors, though not identical. Additionally, Landsat 8 shares spatial resolution and temporal coverage with past sensors enabling continued study of urban growth of cities, health and disturbance of forests, recession of the world's glaciers, and water supply and productivity of agriculture. Critical to establishing a link between the new, existing and past sensors is validating prelaunch radiometric calibration. This work provides early on-orbit calibration results from vicarious methods including intercalibration with other satellite, airborne and ground-based sensors.

8866-54, Session 11

SNPP VIIRS spectral bands co-registration and spatial response characterization

Guoqing Lin, INNOVIM (United States) and NASA Goddard Space Flight Ctr. (United States); James C. Tilton, Robert E. Wolfe, NASA Goddard Space Flight Ctr. (United States); Krishna P. Tewari, INNOVIM (United States) and NASA Goddard Space Flight Ctr. (United States); Masahiro Nishihama, Sigma Space Corp. (United States) and NASA Goddard Space Flight Ctr. (United States)

Spatial response has been quantified in terms of field of view (FOV), modulation transfer function (MTF) or horizontal spatial resolution (HSR) derived from line spread functions (LSFs) measured in the along-track and cross-track directions. Band-to-band co-registration (BBR) has been quantified in terms of pixel overlap from one band to another, with mis-registration of line of sight (LOS) in fractions of specified HSR.

These parameters had been evaluated in the worst case scenario, in the non-aggregation zones near the start and end of scan, for requirement compliance. They have neither been evaluated on-orbit nor in the 2-sample and 3-sample aggregation zones towards the center of scan, which will be presented in this paper. This paper also quantifies spatial response in alternative terms such as ensquared energy (EE) and integrated out-of-pixel (IOOP) response, and BBR based on pre-launch measured values of FOV, HSR and overlapped LSFs between corresponding spectral bands.

8866-55, Session 11

Modeling SNPP VIIRS reflective solar bands optical throughput degradation and its impacts on the relative spectral response

Ning Lei, Zhipeng Wang, Sigma Space Corp. (United States); Xiaoxiong Xiong, NASA Goddard Space Flight Ctr. (United States)

Right after the opening of the NADIR door of the Visible/Infrared Imager/Radiometer Suite (VIIRS) aboard the Suomi National Polar-orbiting Partnership (SNPP) satellite, it has been observed that the detector gains of the near infrared (NIR) bands have decreased much faster than expected. This large decrease is attributed to the mirror reflectance degradation of the Rotating Telescope Assembly (RTA). We have established a physical model to describe the mirror reflectance degradation. In this presentation, we use the physical model to fit the observed data to update the model parameter values and the degradation projection. We have adjusted our original model slightly to address the additional optical throughput degradation for the short wave infrared (SWIR) bands, which occurred right after the spacecraft Sun Point anomaly (orbits 2101-2133). The RTA optical throughput degradation and the additional throughput degradation after the Sun Point anomaly for the SWIR bands are not constant across the optical wavelength and therefore impact on a detector's relative spectral response (RSR). Using the model, we establish the degradation versus wavelength curve at any orbit and use the curve to compute the associated impact on the RSR. We further use this degradation modulated RSR to compute the impact on sensor calibration and the Earth View reflectance at the Sensor Data Record (SDR) level.

8866-56, Session 11

Effect of the SDSM detector relative spectral response in determining the degradation of the SNPP VIIRS solar diffuser reflectance

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The Visible/Infrared Imager Radiometer Suite (VIIRS) instrument aboard the Suomi National Polar-orbiting Partnership (SNPP) satellite performs its radiometric calibration in the reflective solar bands wavelength region primarily through observing the sunlight scattered from the onboard Solar Diffuser (SD). The reflectance of the SD degrades over time. The degradation is determined by comparing the irradiance of the sun-lit SD with that of the Sun through the onboard Solar Diffuser Stability Monitor (SDSM). The out-of-band relative spectral response (RSR) of the SDSM detectors, if large enough, can lead to a non-negligible bias to the originally determined SD degradation coefficient. The RSR integrates the photons (scattered from the SD) over a wide range of wavelengths to yield the detector signal. As a result, the SD degradation coefficient is more accurately described by an integral (over wavelength) equation. In this presentation, we establish a methodology to solve this particular type of integral equation and apply the methodology to determine the bias.

8866-57, Session 11

Improving the characterization and performance of the Suomi-NPP/VIIRS solar diffuser stability monitor

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The Visible/Infrared Imager Radiometer Suite (VIIRS) instrument on Suomi-NPP performs its primary radiometric calibration through observations of sunlight reflected off the Solar Diffuser (SD). The optical performance of the SD degrades with exposure to short-wavelength UV light. Therefore, VIIRS includes the Solar Diffuser Stability Monitor (SDSM) to monitor the optical performance of the SD. The SDSM acts as a ratioing radiometer that compares the irradiance observed off the SD to that of direct observations of the Sun simultaneously in eight visible/near-IR (VisNIR) bands. These observations yield the H-factors which are used by the SD algorithm to determine the detector gains of the main VIIRS VisNIR bands. In this paper we evaluate several potential improvements to the algorithm used to determine the H-factor from the SDSM observations. First, we include a correction for the effects of the out-of-band response of the SDSM detectors into the calculation of H-factors. Another possible improvement is an update to the transmission functions for both the Sun view and Solar Diffuser view based on the both the yaw-maneuver data and the nominal mission data. We also consider methodologies to expand the amount of useful data recovered per SDSM event, helping correct for the slight misalignment of SDSM optics. Finally, we continue to track the on-orbit degradation of the SDSM detectors and give an estimate of the long-term performance of the SDSM. For each potential improvement, we report on the net effect of the change on the baseline H-factor trending and the H-factor uncertainty.

8866-58, Session 11

NPP VIIRS on-orbit calibration using the Moon

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The Visible Infrared Imager Radiometer Suite (VIIRS) on-board the Suomi National Polar-orbiting Partnership (NPP) satellite was launched on October 28, 2011. VIIRS has been scheduled to view the Moon approximately monthly through a spacecraft roll maneuver after the opening of the nadir door on November 21, 2011 through the Space View (SV) port to monitor the long-term radiometric stability of its Reflective Solar Bands (RSB). There are also about four lunar intrusions into VIIRS SV per month in about nine months every year. The lunar irradiance observed by VIIRS depends on the viewing geometry. In each VIIRS lunar observation, the Moon is viewed in multiple scans. The lunar irradiance of a VIIRS RSB can be derived from the response of all of its detectors in one of the scans, each of which fully covers the Moon. It can also be calculated from the response of four adjacent scans or by all detectors in multiple scans. The calculated values of the lunar irradiance from different numbers of scans and different detectors are compared and the uncertainty of the calculated VIIRS lunar irradiance is estimated. The influence of the instrument temperature on the lunar irradiance is corrected. With the geometric effect corrected using the ROLO lunar model's prediction and prelaunch calibration coefficients applied, the calculated lunar irradiance can be used to track on-orbit gain change for VIIRS RSB, the inverse of which is the calibration coefficient, F factor, that can also be derived from the Solar Diffuser (SD) calibration. From the lunar calibrations, the calibration coefficient is derived for each band, detector, and Half-Angle Mirror (HAM) side. In this paper, we report our results using the lunar observations to track the VIIRS RSB gain changes since first lunar observation in January, 2012 and to compare the gain changes derived from both lunar and SD calibrations. It is shown that the gain, the inverse of the calibration coefficient, degrades with time

and the degradation is strongly band (wavelength) dependent. The largest degradation occurs at near infrared bands while visible bands have much smaller degradation. The differences between the calibration coefficients derived from the lunar observations and those obtained from the SD calibration are within 0.5% for most bands and within 2% short wavelength bands.

8866-59, Session 11

A synthesis of VIIRS solar and lunar calibrations

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The NASA VIIRS Ocean Science Team (VOST) has developed an independent calibration of the SNPP VIIRS moderate resolution reflective solar bands using solar diffuser observations to date and lunar observations through May 2013. The trends show a divergence between the solar and lunar calibration time series, with a greater sensitivity loss in the blue band lunar trends than in the solar trends. Possible causes of the divergence include uncertainties in the solar diffuser stability monitor trending of the solar diffuser BRDF. Assuming that lunar trending is more reliable than solar trending, the VOST has developed a synthesis approach to the on-orbit calibration of VIIRS that uses band-averaged lunar trends to correct the solar time series. Solar observations continue to provide information regarding detector-to-detector and mirror-side response variations. Solar trending also shows a stronger focal plane temperature dependence than expected from the prelaunch instrument characterization testing, leading the VOST to derive a revised set of focal plane temperature correction coefficients. Implementation of the lunar-corrected, solar-derived calibration in ocean data processing shows ocean surface reflectance trends that are more consistent with MODIS observations than surface reflectances derived from the solar-derived calibration alone.

8866-60, Session 12

Improvements of VIIRS and MODIS solar diffuser and lunar calibration

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Both S-NPP VIIRS and Terra and Aqua MODIS use solar diffuser (SD) and lunar observations to calibrate their reflective solar bands (RSB). In addition, a similar solar diffuser stability monitor (SDSM) is used to track the SD on-orbit degradation or change of the SD bi-directional reflectance factor (BRF). On-orbit observations have shown similar wavelength-dependent SD degradation (larger at shorter VIS wavelengths) and SDSM detector response degradation (larger at longer NIR wavelengths) for both MODIS and VIIRS instruments. On the contrary, MODIS scan mirror has shown more degradation in the VIS spectral region and the VIIRS rotating telescope assembly (RTA) mirrors have experienced more degradation in the NIR and SWIR spectral region. As a result, the sensor's relative spectral response (RSR), in-band (IB) and out-of-band (OOB) combined, is modulated. Due to differences between the solar and lunar spectral irradiance, the modulated RSR will have different impact on the SD and lunar calibration. In this paper, we identify all the factors that need to be considered for the improvements of current SD and lunar calibration approaches and examine their impact on the RSB calibration quality. Special efforts will be made to characterize the effects due to SD and SDSM attenuation screen transmission (uncertainty), SD BRF (uncertainty), SD degradation modulated solar spectral irradiance, sensor optics degradation modulated RSR, and SDSM detector (response) degradation modulated RSR.

8866-61, Session 12

SNPP VIIRS thermal band spectral radiance performance through 18 months on-orbit

Chris Moeller, David Tobin, Greg Quinn, Univ. of Wisconsin-Madison (United States)

SNPP, carrying the first VIIRS instrument, was launched on October 28, 2011 with first light on November 21, 2011. The passive radiative cooler doors were opened on January 18, 2012 allowing the cold focal planes (S/MWIR and LWIR) to cool to the nominal operating temperature of 80K. After an early on-orbit functional checkout period, an intensive Cal/Val (ICV) phase began in the spring 2012. During the ICV, tasks to evaluate various components of the VIIRS radiometric performance have been in process, with data collection and analysis now approaching a one year milestone.

This paper will provide findings of ICV tasks assigned to the University of Wisconsin, including Sensor Data Record (SDR) spectral radiance performance, out-of-band spectral performance, and the Response vs. Scan (RVS) performance of the VIIRS Half Angle Mirror (HAM). The tasks leverage matchups of SNPP VIIRS thermal band earth scene observations with those of CrIS and Metop-A IASI. VIIRS-CrIS globally distributed matchups exceed 100,000 per day, while VIIRS-IASI SNO matchups are limited to high latitudes in each hemisphere at a rate of a few thousand per year. The matchups, with spatial and spectral dependencies removed, establish the daily baseline performance of all VIIRS TEB relative to the other sensors, as well as provide insight into long term performance trends. The first year of comparisons suggest that VIIRS TEB are performing within or very near specification, and show excellent performance stability over the existing data record.

8866-62, Session 12

VIIRS thermal emissive bands on-orbit calibration coefficient performance using vicarious calibration results

David I. Moyer, The Aerospace Corp. (United States); Chris Moeller, Univ. of Wisconsin-Madison (United States); Frank De Luccia, The Aerospace Corp. (United States)

The Visible-Infrared Imaging Radiometer Suite (VIIRS) a primary sensor on-board the Suomi-National Polar-orbiting Partnership (SNPP) spacecraft was launched October 28, 2011. It has 22 bands: 7 thermal emissive bands (TEBs), 14 reflective solar bands (RSBs) and a Day Night Band (DNB). The TEBs cover the spectral wavelengths between 3.7 to 12 ?m and have two 371m and five 742m spatial resolution bands. A VIIRS Key Performance Parameter (KPP) is the sea surface temperature (SST) which uses bands M12 (3.7?m), M15 (10.8?m) and M16's (12.0?m) calibrated Science Data Records (SDRs). The TEB SDRs rely on prelaunch calibration coefficients which use a quadratic algorithm to convert the detector's response to calibrated radiance. This paper will evaluate the performance of these prelaunch calibration coefficients using vicarious calibration information from the Cross-track Infrared Sounder (CrIS) also on-board the SNPP spacecraft and the Infrared Atmospheric Sounding Interferometer (IASI) which is on-board a Meteorological Operational (MetOp) satellite. Changes to the prelaunch calibration coefficient's offset term c0 to improve the SDR's performance at cold scene temperatures will also be discussed.

8866-63, Session 12

VIIRS day/night band (DNB) stray light characterization and correction

Steve Mills, Stellar Solutions, Inc. (United States) and Northrop Grumman Aerospace Systems (United States); Stephanie Weiss, Calvin Liang, Northrop Grumman Aerospace Systems (United States)

The Day/Night Band (DNB) on the VIIRS sensor is a panchromatic band that can detect very dim nighttime scenes. After launch of Suomi NPP in October 2011 we observed a gray haze in radiance images with offsets up to 5?10-9 W cm-2 sr-1. Overall this impacts about 25% of nighttime scenes. We considered stray light as the likely cause, and studied calibration data from the space view. We concluded that stray light is entering the VIIRS scan cavity through its nadir door and solar diffuser openings. We also studied the darkest earth scenes without any solar, lunar or artificial illumination, and found that the offset is a function of cross-track pixel, solar angle of incidence (AOI) and detector number. We observed a strong detector dependence causing striping. Dividing scenes into 3 or 4 zones in each hemisphere based on solar AOI, we devised an algorithmic correction based on polynomial fits of the medians of the data for each zone. The correction removed almost all the haze and striping and improved dynamic range by 2 orders-of-magnitude, to as low as 1?10-10 Wcm-2 sr-1, but some striping remains in the twilight region due to extrapolation.

8866-64, Session 12

On the potential to enhance the spatial resolution of the day-night band (DNB) channel of the visible and infrared imaging radiometer suite (VIIRS) for the second joint polar satellite system (JPSS-2) and beyond

James K. McCarthy, Stellar Solutions, Inc. (United States); Eric J. Jacobson, Timothy M. Kilduff, Ronald W. Estes, Raytheon Space & Airborne Systems (United States); Peter A. Levine, SRI International Sarnoff (United States); Steve Mills, Stellar Solutions, Inc. (United States); Chris Elvidge, National Oceanic and Atmospheric Administration (United States); Steven D. Miller, Colorado State Univ. (United States)

The VIIRS DNB channel provides a unique state-of-the-art capability to capture panchromatic visible-light images of the earth over a remarkable dynamic range spanning roughly 7 decades in input radiance, with sufficient sensitivity to produce high quality earth imagery at night even under quarter-moon illumination or less. This paper examines the feasibility and potential benefits of enhancing the spatial resolution of the VIIRS DNB channel for the second JPSS mission and beyond, by modifying the on-chip pixel binning recipe used in the DNB CCD to aggregate detector area within the scan swath. Presently the DNB delivers 16 cross-scan samples similar in size to the detectors in the VIIRS Moderate Resolution Bands. The proposed relatively low-cost enhancement would instead bin the DNB CCD pixels into 32 cross-scan samples, each half as large in track and scan, effectively doubling the spatial resolution of DNB to match that of the VIIRS Imaging Bands at nadir. DNB CCD clocking is performed via the Focal Plane Interface Electronics (FPIE) unit on-board VIIRS; to fully implement the proposed DNB spatial resolution enhancement over the entire cross-track scan swath would require design and hardware modifications to the FPIE to increase certain CCD clock frequencies. This paper explores the scope and feasibility of this option, alongside other options that (if constrained to use the existing FPIE design with no changes) would not provide the enhanced DNB spatial resolution all the way out to the edges of the cross-track scan, and the potential impacts on DNB imagery products and applications.

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8867-1, Session 1

Infrared remote sensing of planetary surfaces: overview, outstanding questions, and prospects *(Invited Paper)*

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We own a major part of our knowledge about the surface composition and structure of solid planetary surfaces infrared imaging and Fourier transform spectroscopy. Basing on these methods it succeeds to observe the single planetary objects in a global geo-scientific content. The topic of infrared surface studies are mineralogical composition analyses, measurement of surface temperature, thermal inertia and photometric observation of the surface regolith texture. The comparison of infrared with photogeologic data forms the essential basis for comparative studies in planetology. The present paper summarizes outstanding results by examples of ESA experiments like VIRTIS on Venus Express and Rosetta, and PFS on Mars Express, MERTIS on Bepi Colombo, and provides an outlook for future plans. The instruments are introduced, and the interplay of disciplines like planetology, IR measuring techniques, and space flight engineering is demonstrated. Following this overview the paper summarizes outstanding questions, and prospects in IR remote sensing of planetary surfaces.

Infrared remote sensing provides essential knowledge about the current state of solid planetary surfaces. This allows studying fundamental questions in comparative planetology. The present paper summarizes selected results of spaceborne surface composition analyses, introduces key instruments, and discusses outstanding questions as well as prospects of the infrared method and techniques.

8867-2, Session 1

Pre-launch calibrations of the vis-IR hyperspectral imager (VIHI) onboard BepiColombo, the ESA mission to Mercury *(Invited Paper)*

Fabrizio Capaccioni, Gianrico Filacchione, Giuseppe Piccioni, INAF - IASF Roma (Italy); Michele Dami, Leonardo Tommasi, Iacopo Ficai Veltroni, SELEX Galileo S.p.A. (Italy)

The pre-launch calibration activities of VIHI, the Visible and Infrared Hyperspectral Imager onboard Bepi Colombo/MPO, the ESA cornestone mission to be launched in 2015 to Mercury, are reported here. VIHI (Capaccioni et al., 2010) is one of the three optical channels of the SIMBIO-SYS suite (Spectrometers and Imagers for MPO BepiColombo Integrated Observatory SYStem). The payload, built by an Italy-France consortium, includes also a high spatial resolution and a stereo colour cameras (Flamini et al., 2010). The VIHI imager spectrometer operates in the 0.4-2.0 µm spectral range with a spectral sampling of 6.25 nm/band, covering a FOV of 64 mrad with 256 pixels having each a IFOV of 250 µrad. Since the instrument shall operate in pushbroom mode, these characteristics allow to acquire a 25.6 km-wide swath on ground at 100 m/pixel resolution from a 400 km polar orbit. Before integration in the SIMBIO-SYS suite, the spectrometer undergoes to a cycle of calibration measurements to characterize the spectral, geometrical, spatial and radiometric performances. These calibration activities include also the characterization of the internal calibration unit output which shall be used in flight for the verification of the instrument performances. These activities, currently running in the Selex SE laboratories (Campi Bisenzio, Florence, Italy), are performed using a specific calibration setup, consisting of a dedicated optical bench, which houses different calibration sources, joined to the VIHI pupil. A description of the calibration purposes, setups, measurements and results, will be given.

8867-3, Session 1

MERTIS on BepiColombo: seeing Mercury in a new light *(Invited Paper)*

Jörn Helbert, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Harry Hiesinger, Westfaelische Wilhelms Univ. (Germany); Mario D'Amore, Ingo Walter, Thomas Säuberlich, Gisbert Peter, Gabriele E. Arnold, Alessandro Maturilli, Piero D'Incecco, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

The MErcury Radiometer and Thermal infrared Imaging Spectrometer (MERTIS) is part of the payload of the Mercury Planetary Orbiter spacecraft of the ESA-JAXA BepiColombo mission. MERTIS's scientific goals are to infer rock-forming minerals, to map surface composition, and to study surface temperature variations on Mercury. To achieve these science goals MERTIS combines a imaging spectrometer covering the wavelength range from 7-14 microns with a radiometer covering the wavelength range from 7-40 microns. MERTIS will map the whole surface of Mercury with a spatial resolution of 500m for the spectrometer channel and 2km for the radiometer channel.

The MERTIS instrument had been proposed long before the NASA MESSENGER mission provided us with new insights into the innermost of the terrestrial planets. The discoveries of the MESSENGER fundamentally changed our view of Mercury. It revealed a surface that has been reshaped by volcanism over large parts of geological history. Volatile elements like sulfur have been detected with unexpectedly high abundances of up to 4%. MESSENGER imagined structures that are most likely formed by pyroclastic eruptions in recent geologic history. Among the most exciting discoveries of MESSENGER are hollows – bright irregularly shaped depressions that show sign of ongoing loss of material.

Despite all this new results the MERTIS dataset remains unique and is now more important than ever. None of the instruments on the NASA MESSENGER mission covers the same spectral range or provides a measurement of the surface temperature. The MERTIS will complement the results of MESSENGER. MERTIS will for example be able to provide spatially resolved compositional information on the hollows and pyroclastic deposits – both among the most exciting discoveries by the MESSENGER mission for which the NASA mission can not provide compositional information.

8867-4, Session 1

Pointing and spectral assignemnt design and control for MERTIS

Ingo Walter, Thomas Säuberlich, Matthias Lieder, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Miroslaw Rataj, Space Research Ctr. (Poland); Hans Driescher, Astro- und Feinwerktechnik Adlershof GmbH (Germany); Jörn Helbert, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Harry Hiesinger, Westfaelische Wilhelms Univ. (Germany)

The development of MERTIS, a miniaturized thermal infrared imaging spectrometer onboard of ESA's cornerstone mission BepiColombo to Mercury has been completed. Qualification of the design is followed by the calibration of the instrument showing up first results of the technology used.

Based on subsequent viewing of different targets including on-board calibration sources the push-broom instrument will use a 2-dimensional bolometer detector to provide spatial and spectral information.

Here repetition accuracy of pointing and spectral assignment is supported by the design of instrument components under the restriction

of limited resources. Additionally a concept of verification after launch and cruise phase of the mission was developed.

The article describes how this has been implemented and what the results under environment testing are.

8867-5, Session 1

Developing of MERTIS as an advanced process from the study up to the flight model

Gisbert Peter, Ingo Walter, Jörn Helbert, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Harry Hiesinger, Institut für Planetologie (Germany); Gariele E. Arnold, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

In 2005 a new infrared spectrometer and radiometer for remote sensing of the Mercury has been proposed to ESA, now in 2013 the flight model is integrated, tested and calibrated. The result is a state of the art instrument with better optical performance as required (e.g. SNR (spectrometer) > 500 @ 8µm), lower technical resources as expected (i.e. 3,1kg and <10W), developed on schedule within the required financial budget. A brief description of the instrument design and applied technologies, the operational concept and optical performances are presented. It is shown that an extended model philosophy not only cost but also saves money, especially when almost all components need new technologies for development. An advanced on-board and on-ground software concept speeds up the development process having more time at the end for calibration, which is one of the most important step getting an optimized scientific optical performance (before launch). Furthermore the verification concept by from the designer independent companies helped getting a design with withstands the harsh environmental conditions during launch, thermally in orbit and due to radiation. The paper gives a summary on the development with examples how it was done and what we have learnt.

8867-6, Session 1

Advanced geometrical calibration of the thermal infrared push-broom imaging spectrometer MERTIS based on simulation and testing

Martin Bauer, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

The Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS) onboard the BepiColombo Mercury Planetary Orbiter (MPO) is a state of the art instrument for studies of the surface composition of Mercury. MERTIS is the first spaceborne push-broom spectrometer that allows mapping the Mercury's surface mineralogy in the diagnostic mid-infrared range.

A method for MERTIS geometrics parameter determination based on ray tracing simulation, laboratory testing and synthesis of both is described by this paper. At first geometrical calibration theory and its application for MERTIS is presented. In the following a simulation of ideal MERTIS imaging by ray tracing and results of laboratory testing are presented. Than it is shown how simulation and laboratory testing data are connected to the calibration model and results are discussed. The method of coupled simulation and testing gives a feedback during the calibration process itself and finally makes it more reliable.

8867-7, Session 2

Atmospheric chemistry suite (ACS): a set of infrared spectrometers for atmospheric measurements on board ExoMars trace gas orbiter *(Invited Paper)*

Oleg Korablev, Space Research Institute (Russian Federation) and Moscow Institute of Physics and Technology (Russian Federation); Alexei V. Grigoriev, Space Research institute (Russian Federation); Alexander Trokhimovsky, Space Research Institute (Russian Federation) and Moscow Institute of Physics and Technology (Russian Federation); Yurii Ivanov, Main Astronomical Observatory (Ukraine); Boris Moshkin, Space Research Institute (Russian Federation); Alexei Shakun, Space Research Institute (Russian Federation) and Moscow Institute of Physics and Technology (Russian Federation); Imant I. Vinogradov, Ilya Dzuban, Space Research Institute (Russian Federation); Franck Montmessin, Lab. Atmosphères, Milieux, Observations Spatiales (France)

The ACS package for the ExoMars Trace Gas Orbiter is a part of Russian contribution to the ExoMars mission. On the Orbiter in complements NOMAD investigation and is intended to recover in much extent the science lost with the cancellation of NASA MATMOS and EMCS infrared sounders. ACS includes three separate spectrometers, sharing common mechanical and electrical interfaces.

NIR is a versatile spectrometer for the spectral range of 0.7 – 1.7 ?m with resolving power of 20000. It is conceived on the principle of RUSALKA/ISS or SOIR/Venus Express experiments combining an echelle spectrometer and an AOTF (Acousto-Optical Tuneable Filter) for order selection. NIR will be operated principally in nadir, but also in solar occulations, and possibly on the limb.

MIR is a high-resolution echelle instrument exclusively dedicated to solar occultation measurements in the range of 2.2 – 4.4 ?m targeting the resolving power of 50000. The order separation is done by means of a steerable cross-disperser, allowing instantaneous coverage of two 200-nm ranges of the spectrum. MIR is dedicated to sensitive measurements of trace gases, approaching MATMOS detection thresholds for many species.

TIRVIM is a 2-inch double pendulum Fourier-transform spectrometer for the spectral range of 1.7-17 µm, and apodized resolution varying from 0.2 to 1.6 cm-1. TIRVIM is primarily dedicated to monitoring of atmospheric temperature and aerosol state in nadir, and would contribute in solar occultation to detection/reducing of upper limits of some components absorbing beyond 5 ?m, complementing MIR and NOMAD. Additionally, MIR targets the methane mapping in nadir, using separate detector optimized for 3.3-µm range.

The development status and technical implementation of the instrument will be discussed.

8867-8, Session 2

Remote sensing of planetary atmospheres in the thermal IR: Mars and Venus *(Invited Paper)*

Luidmila Zazova, Alexei V. Grigoriev, Space Research Institute (Russian Federation); Gabriele E. Arnold, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Rainer Haus, Westfälische Wilhelms-Univ. Münster (Germany)

Remote sensing in the thermal IR is an effective method of the planetary atmospheres investigations. IR spectrum with strong absorption bands gives information about the atmosphere layers in a wide range of latitudes. In the atmospheres of Mars and Venus the 15?m CO2 band is the most outstanding. Our work is devoted to the most significant results of IR spectrometry for Mars and Venus, including IRIS Mariner-9 and PFS

Mars Express for Mars and PMV Venera-15 and VIRTIS VEX. We also discuss shortly a possible future work.

8867-9, Session 2

Search for Martian methane with TES data: development of a dedicated radiative transfer code: first results

Giuliano Liuzzi, Guido Masiello, Carmine Serio, Univ. degli Studi della Basilicata (Italy); Sergio Fonti, Francesca Mancarella, Univ. del Salento (Italy); Ted L. Roush, NASA Ames Research Ctr. (United States)

Since methane was first reported in the Martian atmosphere, in 2004, an extraordinary effort has been undertaken to understand its origin, evolution and removal from the atmosphere, on time scales much less than the UV photodestruction rate of ~350 years. Much of the work, using orbital data, so far has focused on the analysis of the data coming from two instruments: the Planetary Fourier Spectrometer (PFS) on the Mars Express, and the Thermal Emission Spectrometer (TES) on the Mars Global Surveyor. Here we focus on the TES data, because of their abundance (several millions of spectra per Martian year), the more extensive spatial coverage, and better spatial resolution. Unfortunately, the spectral resolution of TES (5 and 10 cm-1) is challenging to the detection of methane using the ?4 band centered at 1306 cm-1. For this reason, an accurate atmospheric model, and a reliable radiative transfer code are required, in order to assess the reliability of the methane column abundance retrieval with TES data, and whether methane exhibits a regular seasonal cycle or not. From this perspective, we have developed a dedicated pseudo-monochromatic radiative transfer model, based on a model developed for the analysis of the Earth atmosphere, whose main advantage is the analytical parameterization of the optical depths layer-by-layer, with the ability to calculate the analytical Jacobians with respect to the gas concentrations and to the state vector.

In the present work, the main theoretical elements of this model and the first results are shown.

8867-10, Session 2

The Venus emissivity mapper instrument concept

Jörn Helbert, Nils T. Mueller, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Riccardo Nadalini, Active Space Technologies GmbH (Germany); Suzanne Smrekar, Jet Propulsion Lab. (United States)

The Venus Emissivity Mapper (VEM) is a new instrument concept designed specifically to observe Venus's surface in segments of the near-IR (NIR) spectrum that penetrate the atmosphere with minimal absorption. It builds on experience from analysis of data from Galileo/NIMS, Cassini/VIMS, and especially VIRTIS on Venus Express. Unlike those general-purpose imaging spectrometers, VEM is a hyperspectral mapper focused on observing the surface. It will map the surface in five atmospheric windows between 0.85 and 1.18 microns. In addition, several other bands are used to observe the clouds and water vapor at 0–15 km altitude.

VenusExpress VIRTIS data have already generated significant scientific results about Venus's surface. However, the instrument was not specifically designed for this purpose. The design of VEM will allow imaging Venus with a signal to noise ratio (SNR) at 1.31 ?m that is twice the SNR of 3 sec exposure VIRTIS images. VEM's band-center and width-scatter is roughly 5 times less than VIRTIS.

8867-11, Session 3

In-orbit performance of the AVHRR, HIRS, and AMSU-A instruments onboard the MetOp-A and MetOp-B satellites *(Invited Paper)*

Douglas R. Battles, HE Space Operations GmbH (Germany); Robert W. Lambeck, MEI Technologies, Inc. (United States); Abelardo Perez-Albinana, European Space Research and Technology Ctr. (Netherlands); Helmut Bauch, Telespazio VEGA Deutschland GmbH (Germany); Jörg Ackermann, European Organisation for the Exploitation of Meteorological Satellites (Germany)

The MetOp series of satellites constitute the space segment for the EUMETSAT Polar System (EPS), the European contribution to the Initial Joint Polar System, being developed in co-operation with the National Oceanic and Atmospheric Administration (NOAA) of the USA, to provide meteorological data from the polar orbit.

The first MetOp satellite was launched on 19 October 2006 on a Soyuz launcher from the Baikonur Cosmodrome in Kazakhstan. Following the successful completion of the commissioning campaign, the MetOp-A satellite and its ground segment were declared operational by both agencies, NOAA and EUMETSAT, during the summer of 2007. Now already exceeding its mission lifetime goal of five years in service, the performance trends presented in this paper take on special significance. The MetOp-B satellite was launched on 17 September 2012, so this paper will focus on the long-term performance trends on MetOp-A and draw comparisons with the early performance results on MetOp-B.

The Advanced Very High Resolution Radiometer (AVHRR), the High-resolution Infrared Radiation Sounder (HIRS) and the Advanced Microwave Sounding Unit-A (AMSU-A) instruments constitute the operational meteorological payload provided by NOAA that, in addition to the EUMETSAT provided Microwave Humidity Sounder (MHS), is flown on both the NOAA Polar Orbiting Satellites (POES) and the EUMETSAT MetOp satellites.

It is well known that the varying geometrical relationships between the Sun and the Earth throughout the year affect to some degree the performance of the instruments onboard Earth orbiting satellites. Following the commissioning of MetOp-A, EUMETSAT and NOAA have continued monitoring the long term trends in in-orbit performance of AVHRR, HIRS and AMSU-A. The data acquired since the launch of the satellite has allowed studying how the yearly seasonal variations, as well as aging, have affected the instrument performance. This paper presents the evolution of the performance of the AVHRR, HIRS and AMSU-A for more than six years since the launch of the Metop-A satellite, as well as the early performance results for MetOp-B.

8867-13, Session 3

The SpaceWire-based thermal infrared imager system for asteroid sample return mission HAYABUSA2

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Thermal infrared imager system is developed for HAYABUSA2, which is planned to be launched in 2014 and aims at sample-return from a C class near-Earth asteroid 1999JU3 considered to contain organic or hydrated materials. The system consists of a thermal-infrared imager (TIR) and a digital electronics, which is used not only for the scientific investigation of

physical properties of the asteroid surface, but also for the assessment of landing site selection and safe descent operation onto the asteroid surface with in situ measurement.

Since round trip communication time between the asteroid and the Earth is more than thirty minutes, onboard automatic data processing function and high speed data recording capability are provided to exploit the limited downlink capacity which is up to 32kbps.

TIR adopts an uncooled bolometer with 320 x 240 effective pixels. Image operations as multiple images summation, dark image subtraction, and the compensation of dead pixels are processed onboard. A processing module is connected to sensor interfaces through SpaceWire in order to provide deterministic processing time. Data compression is also provided to reduce restriction on storage capacity and operation time, which provides the equivalent compression ratio as JPEG2000 in 1/30 processing time in average. A high speed data recorder is also connected through SpaceWire in 50Mbps in order to record TIR data in parallel with other sensor data.

The modularity of SpaceWire enables to use as built devices for TIR and inherits the same design as the long-wavelength infrared imager developed for the Venus climate orbiter Akatsuki.

8867-14, Session 3

Space-based carbon monitoring by GOSAT and GOSAT-2: towards better accuracy of Xco2 observation

Hiroshi Suto, Akihiko Kuze, Kei Shiomi, Masakatsu Nakajima, Japan Aerospace Exploration Agency (Japan)

To observe the global column concentration of carbon dioxide (CO2) and methane (CH4) from space, the Greenhouse gases Observing SATellite (GOSAT) was launched on January 23, 2009, and has started the operational observation. Thermal and Near Infrared Sensor for Carbon Observation – Fourier Transform Spectrometer (TANSO-FTS) has been continuously measuring CO2 and CH4 distributions globally, and the retrieved column CO2 and CH4 data have been distributed to the public. Over four-years operational periods, the useful scientific data sets and interesting articles for carbon source/sink evaluation were produced and published, and these results have been supporting to well understanding of carbon cycle. Currently, the importance of space-based carbon observation has been approved and desired the continuous observation in toward. Through the TANSO-FTS operation with the radiometric, geometric and spectroscopic characterizations, we learned how to improve the accuracy of XCO2 and XCH4 based on short-wavelength FTS. The correction procedures for micro-vibration from companion components, non-linear response of analogue and digitizing circuit are key role on the current on-board operating TANSO-FTS. On instrumental aspects, the robustness and improvements will be required on the future mission. The retrieval accuracy of XCO2 by GOSAT spectra is around 2 ppm, which is much smaller than 4 ppm of the GOSAT mission target. To elucidate the carbon cycle more precisely, our experiences have to be summarized and applied in the future missions. To continue and improve the space-based carbon monitoring, the conceptual study of follow-on mission has started and will be presented.

8867-15, Session 3

A Doppler-modulated gas correlation approach for measuring neutral temperatures and wind in the upper atmosphere

Larry L. Gordley, Benjamin T. Marshall, GATS, Inc. (United States)

A new approach to measuring wind and temperature is under development that could revolutionize our ability to monitor wind and neutral temperature in the upper atmosphere. Using a Doppler modulated gas filter correlation technique, wind and temperature can be measured simultaneously from low Earth orbit, continuously from 15 km to over 200 km, on one second time intervals, both day and night. A constellation of six of these dual-sided Doppler Wind and Temperature Sensors (DWTS) on small-sat platforms could provide nearly real time global temperature and wind fields. The DWTS technique, measurements and weather forecast benefits are discussed. A microsoft Power-Point tutorial of the technique can be accessed at http://www.gats-inc.com/projects_dwts.htm.

8867-40, Session 3

A two-laser beam technique for improving the sensitivity of low frequency open path tunable diode laser absorption spectrometer (OP-TDLAS) measurements

Israa L. Mohammad, Univ. of Arkansas at Little Rock (United States) and Univ. of Mustansiriyah (Iraq); Gary T. Anderson, Youhua Chen, Univ. of Arkansas at Little Rock (United States)

Open path tunable diode-laser absorption spectroscopy (OP-TDLAS) is a promising technique that is proposed for detecting low concentrations of possible biogenic gases on Mars. This technique determines the concentration of a gas by measuring the amount of laser light absorbed by molecules at a specific wavelength that is characteristic of those molecules. One of the major factors limiting sensitivity in the TDLAS systems operating at low modulation frequencies is 1/f noise. 1/f noise is minimized in many spectroscopy systems by use of high frequency techniques. However, these techniques use complex instruments that include reference cells and other devices for calibration, making them relatively large and bulky. We are building a spectroscopy system for space applications that requires small, low mass and low power instrumentation, making the high frequency techniques unsuitable. This paper explores a new technique using two laser beams to reduce the affect of 1/f noise and increase the signal strength for measurements made at lower frequencies. In this method, two lasers are excited at slightly different frequencies. An algorithm is then used to estimate the noise in the second harmonic from the combined spectra of both lasers. This noise is then subtracted from the signal to give a more accurate measurement of gas concentration. The error in estimation of 1/f noise is negligible as it corresponds to noise level made at much higher frequencies. Simulation results using ammonia gas and two lasers operating at 500 and 510 Hz respectively shows that this technique is able to decrease the error in estimation of gas concentration to 1/6 its normal value.

8867-34, Session PMon

Influence of radiation energy transfer on boundary layer temperature drops

Tomaz B. Kranjc, Joe Peternelj, Univ. of Ljubljana (Slovenia)

The influence of thermal radiation on wall surface temperatures in a typical conjugate heat transfer problem is studied. Free convective heat transfer, accounted for phenomenologically through the introduction of heat transfer coefficients, is supplemented by surface thermal radiation. The calculations, presented for cubical enclosure exposed on two sides to solar radiation, clearly indicate that surface radiation can change significantly the surface temperatures which, in general, are reduced with increasing emissivities of the walls. In particular, in the case of small convection heat transfer coefficients, small thermal transmittances of the walls and high values of emissivities, the temperature difference across the temperature boundary layers adjacent to the walls could even be reversed.

8867-35, Session PMon

Wavefront recovery algorithm in a vectorial shearing interferometer

Beethoven Bravo-Medina, Guillermo Garcia-Torales, Univ. de Guadalajara (Mexico); Ricardo Legarda-Sáenz, Univ. Autónoma de Yucatán (Mexico); Jorge L. Flores-Nuñez, Univ. de Guadalajara (Mexico)

Vectorial shearing interferometer is able to select variable shear and tilt along any wavefront direction. This system is self-referenced and with variable sensibility.

We proposed this instrument to measure a phase object without rotational symmetry. Phase recovery is implemented by a Fourier-based algorithm and spatial unwrapping methods.

We show results emphasizing the advantage in the easier selection of fringe density and orientation of the directional derivative for a specific optical element.

8867-36, Session PMon

Measurement of phase objects by the use of color phase-shifting technique

Oscar E. Castillo, Univ. de Guadalajara (Mexico); Ricardo Legarda, Univ. Autónoma de Yucatán (Mexico); Jorge L. Flores-Nuñez, Guillemo Garcia-Torales, Univ. de Guadalajara (Mexico)

A simple technique for wavefront measurement is presented. This technique is based on the use of a computer display (LCD monitor) to generate color fringe patterns, which are imaged by a single-CCD color camera; whereas a phase object is placed in the ray path for imaging. The ray deflections distort the image of the pattern. By measuring this distortion, the gradients of the phase change caused by the object can be obtained. For the evaluation of the acquired fringe patterns, we use a classical phase-shifting technique encoded in a single color image displayed by the monitor. Therefore, this proposed technique permits real-time object shape measurement. Experiments are presented to demonstrate the success of this technique.

8867-37, Session PMon

Spectral interrogation of several-hundred-years old paintings with a broadband IR camera

Marija Strojnik Scholl, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

We develop a theory to compare the signal-to-noise ratio of detected details with narrow and broad-band IR illumination and detection.

8867-38, Session PMon

Advantages of placing a segmented mirror of the type, the Great Mexican Telescope, on the Moon to detect extrasolar planets

Gonzalo Páez, Marija Strojnik Scholl, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

In the Early nineties, we proposed placing a segmented telescope on the moon to detect the Extra-solar planets. Since that time, we demonstrated that mm region is highly advantageous for planet detection in an inetrferometric configuration. It may even be incorporated on the surface of the Earth, on a high mountain, such as The Great Mexican Telescope, near Puebla, Mexico. We evaluate the performance improvements that may be achieved in the absence of Earth atmosphere.

8867-16, Session 4

ACE-FTS on SCISAT: 10th year on-orbit anniversary *(Invited Paper)*

Marc-André Soucy, Henry L. Buijs, Richard L. Lachance, ABB Analytical Measurement (Canada)

The Atmospheric Chemistry Experiment (ACE) is a mission on-board the Canadian Space Agency's SCISAT-1. ACE consists of a suite of instruments consisting of an infrared Fourier Transform Spectrometer (FTS) coupled with an auxiliary 2-channel visible (525 nm) and near infrared imager (1020 nm). A second instrument, MAESTRO, is a spectrophotometer covering the near ultra-violet to the near infrared. In combination, the instrument payload covers the spectral range from 0.25 to 13.3 ?m. The intent of the ACE mission has been to measure the chemical and dynamical processes that control the distribution of ozone in the upper troposphere and stratosphere. ACE measures the vertical distributions of more trace gases than any other instrument as well as polar stratospheric clouds, aerosols and temperature by solar occultation from low earth orbit. A high inclination (74°), low earth orbit (650 km) provides coverage of tropical, mid-latitude and Polar Regions. Detailed and sensitive vertical distribution of trace gases help to better understand the chemical processes not only for ozone formation and destruction but also other dynamic processes in the atmosphere. The ACE/SCISAT-1 satellite was successfully launched by NASA on August 12, 2003.

This paper presents the heritage and development history of the ACE-FTS instrument. Design challenges and solutions will be related. The actual on-orbit performance is presented, and the health status of the instrument payload is discussed. Potential future follow-on missions are finally introduced. After ten years of fruitful operation in orbit, the SCISAT mission has been the source of over 250 scientific papers.

8867-17, Session 4

Progress in development of tropospheric infrared mapping spectrometers (TIMS): geostationary greenhouse gas (GHG) application *(Invited Paper)*

John B. Kumer, Richard L. Rairden, Aidan E. Roche, Lockheed Martin Space Systems Co. (United States)

We review development of the TIMS beginning in the early part of the decade and up to preliminary results of work in progress. We describe a geostationary application (geoCARB) at near PDR maturity for mapping CO_2, CH_4 and CO column mixing ratios on continental scale areas (e.g., Australia and East Asia) several times per day on contiguous samples with spacing the order 3 km at the sub satellite point. Measurements per footprint are expected to be acquired with median mission SNRs >> 300, 300 and 240 in the traditional spectral regions (e.g., OCO and TANSO-FTS on GOSAT) for CO_2, namely the O_2 A-band, and the weak and strong bands of CO_2 near 1.61 and 2.06 microns; and >> 200 in a region near 2.32 microns for CO and CH_4.The resolving powers are 15000, 15000, 11000 and 11000 in the 4 regions, respectively. Given this performance the median mission retrieval for CO_2, CH_4 and CO column mixing ratio is expected to be considerably better than 0.7, 1.0 and 10.0%, respectively. These measurements over several years would provide a break through reduction in the uncertainty and attribution for the sources of CO_2, CH_4 and CO within the large geostationary field of regard of the geoCARB.

8867-18, Session 4

Determination of technical readiness for an atmospheric carbon imaging spectrometer

Joseph Mobilia, John B. Kumer, Alice L. Palmer, Kevin A. Sawyer, Yalan Mao, Jason A. Mix, Ted C. Nast, Charles S. Clark, Roel W. H. van Bezooijen, Antonio L. Magoncelli, R. Baraze, David L. Chenette, Lockheed Martin Space Systems Co. (United States)

The geoCARB sensor uses a 4-channel slit-scan push broom slit-scan infrared imaging grating spectrometer to measure the absorption spectra of sunlight reflected from the ground in narrow wavelength regions. The instrument is designed for flight at geostationary orbit to provide continual monitoring of greenhouse gas over continental scales, several times per day, with a spatial resolution of a few kilometers. The sensor provides multiple daily maps of column-averaged mixing ratios of CO2, CH4, and CO over the regions of interest, which enables flux determination at unprecedented time, space, and accuracy scales. The geoCARB sensor development is based on our experience in successful implementation of advanced, space deployed optical instruments for remote sensing. A few recent examples include the Atmospheric Imaging Assembly (AIA) and Helioseismic and Magnetic Imager (HMI) on the geostationary Solar Dynamics Observatory (SDO), the Space Based Infrared System (SBIRS GEO-1) and the Interface Region Imaging Spectrograph (IRIS), along with sensors under development, the Near Infared camera (NIRcam) for James Webb, and Global Lightning Mapper (GLM) and Solar UltraViolet Imager (SUVI) for the GOES-R series. The Tropospheric Infrared Mapping Spectrometer (TIMS), developed in part through the NASA Instrument Incubator Program (IIP), provides an important part of the strong technological foundation for geoCARB. The presentation discusses subsystem heritage and technology readiness levels for these subsystems. The system level flight technology readiness and methods used to determine this level are presented along with plans to enhance the level.

8867-19, Session 4

geoCARB design, maturity, and geostationary heritage

Kevin A. Sawyer, Howard C. Holmes, Alice L. Palmer, John B. Kumar, Ted C. Nast, Joseph Mobilia, Scott W. Miller, Lockheed Martin Space Systems Co. (United States)

Our companion paper 'Progress in development of…TIMS: geostationary…GHG application' describes geoCARB performance and science. Here we describe a geoCARB design study leading to near PDR maturity. It is based on our rich heritage (AIA and HMI on SDO, SBIRS Geo-1 and upcoming GLM on GOES-R) of successfully building and deploying optical instruments to geostationary. Heritage includes experience and well developed specifications for near a-thermal carbon fiber honeycomb composite optical benches and optomechanical design forms that utilize a "family" of mounts for nearly any type of optical element. The geoCARB approach utilizes composite optical benches and bipod flexures to fully kinematically mount optics. Tooling for alignment and staking of all elements is integral to the design and is "removed before flight" for mass minimization. GeoCARB requires a cryogenic region for focal planes and spectrometers but front end optics and main structure may run much warmer. A sub-bench with a local cold box attached is used for implementation. A star tracker is used for geoCARB posteriori geolocation including pseudo-diurnal thermal distortion characterization. It is kinematically mounted by low conductance thermal isolators directly on to the low expansion high stiffness composite bench that defines the master optical surfaces including the scanning mirrors. Its camera heads thermal load is routed away from the bench via radiation or heat pipes. Use of kinematic mounting is advantageous for low thermal conduction designs. Honeycomb composites enable the design's low thermal mechanical distortions. Lockheed Martin and the Author have a deep, successful heritage in this design skill.

8867-20, Session 4

The capabilities, performance, and status of the SOFIA first-generation instruments

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The Stratospheric Observatory for Infrared Astronomy (SOFIA) is an airborne observatory, carrying a 2.5 m telescope onboard a heavily modified Boeing 747SP aircraft. SOFIA is optimized for operation in the infrared spectrum, much of which is obscured for ground-based observatories by atmospheric water vapor. The first generation SOFIA instrument complement consists of seven instruments: EXES (Echelon-Cross-Echelle Spectrograph), FIFI-LS (Far-Infrared Field-Imaging Line Spectrometer), FLITECAM (First Light Infrared Test Experiment CAMera), FORCAST (Faint Object InfraRed CAmera for the SOFIA Telescope), GREAT (German Receiver for Astronomy at Terahertz Frequencies), HAWC (High-resolution Airborne Wideband Camera), and HIPO (High-speed Imaging Photometer for Occultations). EXES is a 5 µm-28 µm high-resolution spectrograph, being developed at UC Davis and NASA ARC. FIFI-LS is a 42 µm-210 µm integral field imaging grating spectrometer, being developed at the University of Stuttgart. FLITECAM is a 1 µm-5 µm wide-field imager with grism spectroscopy, developed at UCLA. FORCAST is a 5 µm-40 µm imager with grism spectroscopy, developed at Cornell University. GREAT is a heterodyne spectrometer providing high-resolution spectroscopy in several bands from 60 µm-240 µm, developed at the Max Planck Institute for Radio Astronomy. HAWC is a 50 µm-240 µm imager, developed at the University of Chicago, and undergoing an upgrade at JPL to add polarimetry capability and a substantially larger GSFC detector. HIPO is a 0.3 µm-1.1 µm imager, developed at Lowell Observatory. We describe the capabilities, performance, and status of each instrument, highlighting results obtained using FORCAST, GREAT, and HIPO during SOFIA Early Science observations conducted in 2011.

8867-21, Session 4

Metop-B AVHRR IR channel post-launch calibration and verification tests

Tiejun Chang, ERT, Inc. (United States); Xiangqian Wu, National Oceanic and Atmospheric Administration (United States); Fuzhong Weng, National Environmental Satellite, Data, and Information Service (United States)

Meteorological Operational (METOP)-B spacecraft was launched on September 17, 2012, and the Advanced Very High Resolution Radiometer

(AVHRR) IR channels were activated October 18. AVHRR instrument has been tested and characterized pre-launch under thermal vacuum (TV) condition by the instrument vender. The instrument dynamic range, noise equivalent differential temperature (NEDT), and nonlinear response have been characterized in the test. Basing on the TV test data, the calibration coefficients are generated for post-launch. Currently, a radiance based nonlinear correction algorithm is used for L1B data. The on-orbit verification tests have been performed to verify the instrument response and performance, including the dynamic range, NEDT, on-board blackbody (BB) temperature, linear gain, and instrument status from the telemetry data. The post-launch Cal/Val test is to improve the calibration accuracy and enhance the L1B data quality. These tests include stray light analysis, instrument gain verification, and uncertainty assessment. The stray light impact on the calibration is estimated as 0.2% for 11 um channel, 0.3% for 12 um channel, and 3% for 3.7um channel. Some inter-comparison techniques are applied to verify the radiance and brightness temperature from L1B data. One test is planned to compare AVHRR IR channel radiances with the radiance derived from Infrared Atmospheric Sounding Interferometer (IASI) measurement once IASI data is available. The calibration uncertainty assessment will also be presented, including the impact of BB radiance error induced by the BB temperature uncertainty and non-perfect BB emissivity, and the impact from the calibration coefficient uncertainties.

8867-22, Session 4

Holographic substrate-guided spectrometer for atmospheric sensing

Fedor Dimov, Xiaowei Xia, Jun Ai, Neven Rakuljic, Chris Griffo, Engin Arik, Luminit LLC (United States)

Advances in oxygen A-band spectrometers are particularly important with atmospheric radiation measurements. Both simulations and short-field deployments using the oxygen A-band (at ~770 nm) have demonstrated that the path-length distribution of solar photons respond strongly to variations in the opacity and spatial distribution of clouds in both the vertical and horizontal directions. For field applications, existing low-resolution (3.3 nm to 10 nm) A-band spectrometers with a set of optical filters or prisms are inherently more robust, reliable, and cost-effective than high-resolution grating-based spectrometers (ranging from 2.3 nm for rotating shadow band spectro-radiometers to portions of nanometers), but result in a much lower out-of-band (OOB) rejection ratio, which can affect accuracy. In this paper, we demonstrate a novel holographic A-band multi-channel substrate-guided spectrometer device, based on a novel structure of two reflection substrate-guided-wave based holograms (SGWH) that act as dispersing and imaging elements to enable a sufficient spectral resolution combined with a high OOB rejection ratio. The technology is made very attractive by its significantly lower cost than current similar A-band systems/devices, yet will provide higher light throughput, better OOB rejection ratio, higher resolution at smaller size, and better stability and reliability. The new spectrometer is sensitive to the A-band spectral range from from 757 nm to 775 nm (~18 nm), and has a size 100?50?25 cubic mm. Details of fabrication and experimental testing results (both laboratory and outdoor) will be presented.

8867-23, Session 5

Research on diode pumped acousto-optic Q-switched Tm-doped fiber laser

Qijie Huang, Ting Yu, Yameng Zheng, Jifeng Zu, Weibiao Chen, Shanghai Institute of Optics and Fine Mechanics (China)

Owing to its wide gain spectrum from 1.8 to 2.1 μm, Tm-doped fiber lasers have attracted increasing interests in recent years. Despite its large quantum defect, 790 nm laser diodes directly pumping Tm-doped fiber lasers can have a theoretical 200% quantum efficiency by taking advantage of a highly efficient cross-relaxation process. They have been demonstrated as high-power and highly efficient light sources near 2 μm. High power pulsed Tm-doped fiber lasers are promising sources for many applications, including eye-safe LIDAR, medicine, spectroscopy, remote sensing. In this work, we will report our recent research on the 790 nm laser diodes pumped pulsed Tm-doped fiber lasers. Using an acousto-optic modulator as the Q-switcher, the performance of different pump structure and cavity structure is demonstrated. As short as 29 ns pulse with up to 6.5 kW peak power and 188 μJ pulse energy is obtained at 5 kHz repetition rate by using a short but high doped double-clad fiber. Employing a fiber Bragg grating as reflection coupler, approximately 0.1 nm linewidth pulse with less than 150 ns duration is derived in the further work. The performance of these lasers under different launched pump power and repetition rate is also demonstrated. Such these Q-switched Tm-doped fiber lasers can be potential candidates for applications like LIDAR, medicine or seed of master oscillator power amplification.

8867-26, Session 6

Quantum well, quantum dot, and type-II superlattice infrared detector research at the Jet Propulsion Laboratory *(Invited Paper)*

David Z. Ting, Sir B. Rafol, Sam A. Keo, Alexander Soibel, John K. Liu, Jason M. Mumolo, Cory J. Hill, Arezou Khoshakhlagh, Linda Höglund, Edward M. Luong, Sarath D. Gunapala, Jet Propulsion Lab. (United States)

We present an overview of III-V semiconductor based infrared detector and focal plane array development at the NASA Jet Propulsion Laboratory in recent years. Topics discussed include: (1) The development of broad-band long-wavelength quantum well infrared photodetector (QWIP) for imaging spectrometer applications. (2) The concept and realization of the sub-monolayer quantum dot infrared photodetector (SML-QDIP) as an alternative to the standard QDIP based on Stranski-Krastanov (SK) quantum dots. (3) The mid-wavelength infrared quantum dot barrier infrared detector (QD-BIRD) with extended cutoff wavelength. (4) High-performance type-II superlattice long wavelength infrared detectors based on the complementary barrier infrared detector (CBIRD) architecture.

8867-27, Session 6

High-operating-temperature MWIR detectors using type II superlattices *(Invited Paper)*

Sanjay Krishna, The Univ. of New Mexico (United States)

There is an increasing interest in developing higher operating temperature (HOT) detectors using unipolar barrier structures such as nBn, CBIRD, M-structure, N-structure, pBiBn and cascade structures, to name a few. In this talk, I will review some of the approaches that we have developed in our group nBn, pBiBn and cascade detectors. The performance characteristics of these detectors will be discussed in detail in the presentation.

Acknowledgements: I wish to acknowledge my collaborators (Profs. Brueck/Hayat group at UNM, Dr. Cardimona's group at AFRL, Prof. Perera's group at Georgia State University, Prof. Painter's group at Caltech, Profs. Padilla at Boston College, Drs. Toni Taylor, Rohit Prasankumar, Igal Brener and Ganesh Subramaniam at Center for Integrated Nanotechnology (CINT) and Dr. S.K. Noh and Dr. S.J. Lee from Korean Research Institute of Standards and Science (KRISS). This work would not have been possible with out the hard working members of the research group (Dr. E. Plis, Dr. Y.D. Sharma, Dr. Greg von Winckel, Dr. Zhaobing Tian, Dr. Tom Rotter, S. Myers, , J. Montoya, M. Kutty, B. Klein, G. Fiorante, T. Sandy-Schuler, S. Godoy, M. Zamiri, A. Kazemi, L. Acosta, W. Xing and F. Santiago). Work supported by AFRL, AFOSR, MDA, KOSEF-GRL, DARPA, and NSF

8867-28, Session 6

Lidar multirange focal plane development for docking to the ISS

Philip M. Mayner, Raytheon Co. (United States)

A multi-range focal plane was developed and delivered by RVS for a docking system that was demonstrated on STS-134. This required state of the art focal plane and electronics synchronization to capture nanosecond length laser pulses to determine ranges with an accuracy of less than 1 inch.

8867-29, Session 6

MTF comparisons between mesa and planar MWIR focal plane detector structures

Mitchell O. Perley, Justin Wehner, David A. Buell, Raytheon Vision Systems (United States); Joseph McCorkle, Mark J. Rehfield, Raytheon Space & Airborne Systems (United States); David Williams, Andrew Dixon, Neil R. Malone, Raytheon Vision Systems (United States)

Raytheon Vision Systems (RVS) has developed scanning, high-speed (>3klps), all digital, with on-chip Analog-to-Digital Conversion (ADC), mid-wave infrared (MWIR 3-5mm) focal plane arrays (FPA) with excellent modulation transfer function (MTF) performance. Using secondary ion mass spectrometry (SIMS) data and detailed models of the mesa geometry, RVS modeled the predicted detector MTF performance of detectors. These detectors have a mesa structure and geometry for improved MTF performance compared to planar HgCdTe and InSb detector structures and other similar detector structures such as nBn. The modeled data is compared to measured MTF data obtained from edge spread measurements and shows good agreement, Figure 1. The measured data was obtained using a custom advanced test set with 1µm precision alignment and automatic data acquisition for report generation in less than five minutes per FPA. The measured MTF values of 83 unique parts, Figure 2, had a standard deviation of 0.0094 and a mean absolute deviation of 0.0066 at half Nyquist frequency, showing excellent process repeatability and a design that supports high MTF with good repeatability.

8867-30, Session 7

Thermal monitoring of transport infrastructures by infrared thermography coupled with inline local atmospheric conditions survey *(Invited Paper)*

Jean Dumoulin, IFSTTAR (France)

One of the two main objectives of ISTIMES project was to evaluate the potentialities offered by the integration of different electromagnetic techniques able to perform non-invasive diagnostics for surveillance and monitoring of critical transport infrastructures. Among the EM methods investigated, long term thermal monitoring by uncooled infrared camera is a promising technique due to its dissemination potential according to its low cost on the market.

Infrared thermography, when it is used in quantitative mode (not in laboratory conditions) and not in qualitative mode (vision applied to survey), requires to process in real time thermal radiative corrections on raw data acquired to take into account influences of natural environment evolution with time. But, camera sensor has to be enough smart to apply in real time calibration law and radiometric corrections in a varying atmosphere. So the work presented hereafter deals with a measurement system studied and developed with low cost infrared cameras available on the market coupled with other sensors to feed simplified radiative models running, in real time, on GPU available on small PC.

In that context, an HMI was developed under Linux using OpenSource and complementary pieces of software developed at IFSTTAR i.e. infrared camera drivers. This new HMI called “IrLaW” has various functionalities that let it compliant to be use in real site for long term monitoring. In particular, a weather station and a Global Positioning System (for timing and localization) are synchronized with the infrared camera to correct inline thermal measurements. The whole system can be remotely controlled in wire or wireless communication mode depending on what is the context of measurement and the degree of accessibility to the system when it is running on real site.

Experiments on real infrastructure were carried out and promising results were obtained thanks to post processing analysis by signal and image approaches.

Finally, Web-enabled capabilities were studied and developed thanks to the adoption of open standards (e.g. OGC SWE, OGC CSW etc.) that allow tasking the system to acquire data, on demand and from anywhere, through a web portal access. These new functionalities will be presented and discussed in the paper.

8867-33, Session 7

Absolute calibration of the reflected sunlight from the Moon

Gerald T. Fraser, Steven W. Brown, Claire E. Cramer, Keith R. Lykke, Ping-Shine Shaw, Allan W. Smith, National Institute of Standards and Technology (United States); Thomas C. Stone, U.S. Geological Survey (United States); John T. Woodward, National Institute of Standards and Technology (United States)

We describe a new method for measuring the spectral irradiance of the Moon at visible wavelengths. Our effort builds upon the highly successful Robotic Lunar Observatory (ROLO), which determined a precise model for the time-dependent irradiance of Moon from six years of observations obtained with an imager equipped with a set of narrow-band filters. The ROLO Irradiance Model allows the Moon to be used as a radiometric reference for tracking changes in the absolute responsivity of near-infrared to visible satellite sensors as a function of time to better than 1 %. The goal of the present effort is to improve the absolute radiometric accuracy of the ROLO model, presently estimated at ~ 10 %, to 1 %. Our approach, which uses an integrating sphere at the focal plane of a telescope to direct light from the integrated lunar disk into a stable spectrograph, also eliminates the dependence of the model on measured optical properties of lunar soil samples, required to interpolate between the 23 visible and near-infrared bands measured by ROLO. The new measurements will allow weather, climate, land-surface, and defense satellites to use the Moon as an absolute calibration reference, potentially reducing the impact of disruptions in continuous long-term climate data records caused by gaps in satellite sensor coverage.

8867-39, Session 7

STORM: sounding and tracking observatory for regional meteorology to launch in 2016 *(Invited Paper)*

Gail E. Bingham, Scott M. Jensen, John Ewell, Joel G. Cardon, Utah State Univ. (United States); David J. Crain, GeoMetWatch Corp. (United States); Allen H.-L. Huang, William L. Smith Jr., Henry E. Revercomb, Univ. of Wisconsin-Madison (United States)

Sounding and Tracking Observatory for Regional Meteorology (STORM), a derivative of the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) EDU that was designed, built and tested for NASA by Utah State University (USU) in the early 1990s will be launched on a commercial geostationary satellite in late 2016. STORM combines advanced technologies to observe surface thermal properties and atmospheric weather and chemistry variables in four dimensions.

Large area format Focal Plane detector Arrays (LFPAs) provide near instantaneous large area coverage with high horizontal resolution. A Fourier Transform Spectrometer (FTS) enables atmospheric radiance spectra to be observed simultaneously for all LFPA detector elements, thereby providing high vertical resolution temperature and moisture sounding information. The fourth dimension, time, is provided by the geosynchronous satellite platform, which enables near continuous imaging of the atmosphere's three-dimensional structure. STORM will enhance the polar orbiting imaging and sounding measurements by providing: (1) a direct measure of moisture flux and altitude-resolved water vapor and cloud tracer winds throughout the troposphere, (2) an observation of the time varying atmospheric thermodynamics associated with storm system development, and (3) the transport of tropospheric pollutant gases (i.e., CO and O3).

GMW has entered into a partnership with AsiaSat to host the first STORM sensor on their AsiaSat 9 telecommunications satellite at 122 E over the Asia Pacific area. GMW's business plan is to sell the unique STORM data and data products to countries and companies in the satellite coverage area. GMW plans to place 6 STORM sensors on geostationary telecommunications satellites to provide global hyperspectral sounding and imaging data. Utah State's Advanced Weather Systems Laboratory (AWS) will build the sensors for GMW.

This paper provides an overview of the STORM instrument and the measurement concept. The STORM data will provide data of the same quality as the current LEO satellite sounders (AIRS, CrIS and IASI) but with the ability to track storm development with soundings and images at any desired rate. Wind profiles obtained from a time sequence of STORM water vapor retrieval images will provide additional input to now casting and regional models to supplement synoptic balloon observations.

8868-17, Session PMon

Angle-doppler resolved reflective tomography imaging lidar

Xiaofeng Jin, Luoyang Institute of Electro-Optical Equipment (China); Yi Yan, Luoyang Optoelectro Technology Development Ctr. (China); Peng Zhang, Chunhua Liu, Luoyang Institute of Electro-Optical Equipment (China); Jianfeng Sun, Liren Liu, Shanghai Institute of Optics and Fine Mechanics (China)

Angle-Doppler resolved reflective tomography using single-frequency continuous lasers has been shown to be an image reconstruction, which can be used to recover image information about an object with a non-imaging laser radar system. This paper presents a system of angle-Doppler resolved reflective tomography imaging Lidar. The resulting time-dependent return signal is collected by a non-imaging optical system, which provides a one dimensional signal about the target as a function of Doppler frequency after the short time FFT at each view. The issue between transverse range resolution and the sampling time of single angle is solved. We designed the condition of far-field diffraction in the laboratory, and collected the angle-Doppler reflective projections of the target. Filtered back-projection algorithm was used to reconstruct the cross section of the target. Because of the utilization of coherent detection of coaxial beams, both the imaging S/N ratio and the receiving sensitivity are improved. Due to the simplification in configuration and operations without involving signal phrase processing, this technique has a great potential for applications in extensive Laser radar imaging fields.

8868-20, Session PMon

Imaging resolution analysis using Fourier
slices theorem in reflective tomography laser radar

Yi Sin Yan, Luoyang Optoelectro Technology Development Ctr. (China); Xiaofeng Jin, Luoyang Institute of Electro-Optical Equipment (China); Shuping Zhou, Luoyang Optoelectro Technology Development Ctr. (China); Jianfeng Sun, Liren Liu, Shanghai Institute of Optics and Fine Mechanics (China)

Reflective tomography is one of the most promising high-resolution imaging methods for the remote objects. But in practical application, because of the sampling angle error and limited view of projections in signal collecting process, anisotropic resolution is inevitable and the reconstruction image quality of reflective tomography system degrades. Sampling angle error occurs because the detect angle range is so large that it is difficult to guarantee the consistency of the actual and theory situation, system error and noise can not be excluded. Insufficient projections data problems occur quite frequently because of practical constraints due to the imaging hardware, scanning geometry or target rotation. In this paper, the theoretical imaging resolution derived from Fourier-Slice theorem is presented, computer simulation and experimental verification are also given. Imaging analysis in this paper will make a complement and perfection of the theory in reflective tomography imaging lidar.

8868-1, Session 1

Isolated nanoinjection photodetectors for high-speed and high-sensitivity single-photon detection *(Invited Paper)*

Vala Fathipour, Omer G. Memis, Sung Jun Jang, Robert L. Brown, Iman Hassani Nia, Ryan M. Gelfand, Hooman Mohseni, Northwestern Univ. (United States)

Realization of a large number of emerging technologies such as quantum computing and quantum cryptography have been dependent on the challenging development of highly sensitive single photon detectors (SPDs) with high internal gain, high signal to-noise ratio (SNR) , low jitter, high quantum efficiency and fast response.

Our group has designed and developed a revolutionary new SWIR detector called the nano-injection detector presenting a stable internal amplification while operating at linear regime with low bias voltages. The nano-injector has a high SNR, a stable excess noise factor and exhibits sub-Poissonian noise levels with the Fano noise suppression. In addition, the nano-injector devices can be hybridized into sensitive imagers as they can be formed in high-density arrays and are fully compatible with CMOS technologies due to their low voltage requirements. Furthermore, the high internal amplification of the nano-injection detectors results in high SNR and suppresses later noise contributions such as ROIC noise or preamplifier noise. As such, the nano-injection detectors are viable candidates for SPD and imaging at the short-wave infrared band.

In the first generation of the nano-injector detector, our group developed a high gain low noise SWIR SPD based on a type-II material system at room temperature and bias voltages less than 1 V. We report on a high speed version of the detector that has maintained the excellent gain, low jitter and good noise performance but has significantly enhanced device speed by 5 orders of magnitude. This is achieved by passivating and laterally confining the carrier transportation.

8868-2, Session 1

Comparison of ultimate limits of interband cascade infrared photodetectors and single-absorber detectors

Robert T. Hinkey, Rui Q. Yang, The Univ. of Oklahoma (United States)

Interband cascade infrared photodetectors utilizing multiple discrete stages have been proposed as a means to achieve high performance infrared detectors at high operating temperatures. In this paper, we present a quantitative theoretical comparison of single- and multiple-stage infrared photovoltaic detectors. Specifically, we investigate the ultimate performance limits of infrared detector materials with a given absorption coefficient, diffusion coefficient, and interband generation-recombination properties. We assume detectors with bulk-like absorbers and show how the standard semiconductor transport and recombination equations can be extended to the case of multiple-stage devices. The contribution of both the generation-recombination and diffusion processes to the total current noise is evaluated by using the Ramo-Shockley theorem and the Weiner-Khintchine theorem. This provides a unified noise treatment accounting for both Johnson and shot noise. Using this formalism, we derive analytic expressions for the photocurrent and noise. Comparisons of single- and multiple-stage detectors under several conditions are presented. The magnitude of the improvement possible with the use of multiple stages depends on the number of stages used and the product of the absorption coefficient and minority carrier diffusion length of the absorber material.

8868-3, Session 1

Long-wavelength interband cascade infrared photodetectors with InAs/GaSb superlattice absorbers

Robert T. Hinkey, Lu Li, Hao Ye, Rui Q. Yang, Michael B. Santos, Matthew B. Johnson, The Univ. of Oklahoma (United States)

Improved performance of long-wave infrared (LWIR, 8-12 ?m) detectors may be possible with the use of multiple-stage interband cascade structures. Compared to single-absorber detectors, this type of architecture can achieve higher photon-photocarrier conversion

efficiencies for materials with small absorption coefficients and/or short diffusion lengths. This architecture also increases the diode resistance, thereby making the detectors less susceptible to parasitic noise sources, such as the pre-amplifier.

In this paper, we present our recent study of interband cascade infrared photodetectors capable of detecting in the LWIR region. These structures utilized p-type type-II InAs/GaSb superlattice absorbers, and were grown using molecular beam epitaxy on GaSb substrates. We investigated both two-stage and three-stage devices. In both structures, the first stage had an absorber with a thickness of 570 nm. The subsequent absorber thicknesses were varied across the structures in order to achieve a roughly equal number of absorbed and collected carriers in each stage. At 78 K, the cutoff wavelengths were ~12.8 ?m for the two-stage device and ~11.9 ?m for the three-stage device. The maximum zero-bias responsivities were 0.6 and 0.5 A/W for the two-stage and three-stage devices, respectively. These values are indicative of good carrier collection. However, the ultimate performance of the detectors from both structures was limited by high dark current. We found that despite some mismatch of photocurrent between the stages, the three-stage devices achieved higher values of D* and were able to maintain an observable zero-bias photoresponse for temperatures up to 170 K.

8868-4, Session 1

High-performance SWIR sensing from colloidal quantum dot photodiode arrays

Jay S. Lewis, Ethan J. D. Klem, Chris W. Gregory, Garry B. Cunningham, Dorota S. Temple, RTI International (United States); Arvind I. D’Souza, Ernest W. Robinson, DRS Sensors & Targeting Systems, Inc. (United States); Nibir K. Dhar, Defense Advanced Research Projects Agency (United States); Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

While InGaAs-based focal plane arrays (FPAs) provide excellent detectivity and low noise for SWIR imaging applications, wider scale adoption of systems capable of working in this spectral range is limited by high costs, limited spectral response, and costly integration with Si readout integrated circuits (ROICs). RTI has demonstrated a novel photodiode technology based on IR-absorbing solution-processed PbS colloidal quantum dots (CQD) that can overcome these limitations of InGaAs FPAs. The most significant advantage of the CQD technology is ease of fabrication. The devices are fabricated directly onto the ROIC substrate at low temperatures compatible with CMOS, and arrays can be fabricated at wafer scale. Further, device performance is not expected to degrade significantly with reduced pixel size. This combination of high performance, dramatic cost reduction, and multi-band sensitivity is ideally suited to expand the use of SWIR imaging in current applications, as well as to address applications which require a multispectral sensitivity not met by existing technologies.

We will present the results for both passive detectors fabricated on passive Si substrates and on ROICs. We will discuss recent advances in device architecture and processing that resulted in measured dark currents of 3 nA/cm2 at room temperature and sensitivity to ~1.7 µm. We will show other devices with spectral sensitivity that extends from UV to 2.2 µm. We will present D* for the ROIC-integrated devices and discuss the path forward for further performance improvements.

8868-24, Session 1

Advanced imaging systems programs at DARPA/MTO *(Invited Paper)*

Nibir K. Dhar, Defense Advanced Research Projects Agency (United States)

No Abstract Available

8868-5, Session 2

Effect of electrical contacts on quantum efficiency of near-infrared InGaAs detectors

Xue Li, Heng-jing Tang, Peng Wei, Hai-mei Gong, Tao Li, Shanghai Institute of Technical Physics (China)

InGaAs-based FPAs operated at room temperature are widely used in short wavelength infrared (SWIR) detection systems due to the demand of miniaturization, low cost and high reliability for night vision, spectroscopy, semiconductor wafer inspection, astronomy and military applications. Recently in order to improve the performance and extend wavelength of the detectors, a new type of InGaAs p-i-n photodiodes which consist of a n-type In0.52Al0.48As layer, intrinsic In0.53Ga0.47As absorption layer and p-type In0.52Al0.48As on InP substrate is also studied. I–V characteristics and spectral responses of the detectors were measured and quantum efficiencies of the detectors were investigated by signal and noise measurement system. Quantum efficiency ? of the detector is only 63%. The ideal factor nj and Schottky barrier of the Schottky junction between metals and the p-In0.52Al0.48As capping layer are 1.05 and 0.36eV, respectively, by fitting I-V curve. Schottky-type-like behavior is responsible for the lower quantum efficiency. The ohmic contacts and series resistance of detectors were largely improved by growing the thin p-InGaAs layer on the p-InAlAs layer. Spectral response of detector decreases slightly at the shorter wavelength, which has little effect on the quantum efficiency of the detector. Quantum efficiency of detector reaches up to 90%.

8868-6, Session 2

Embedded plasmonic-enhanced quantum well infrared photodetector

Robert L. Brown, Alireza Bonakdar, Omer G. Memis, Vala Fathipour, Sung Jun Jang, Hooman Mohseni, Northwestern Univ. (United States)

In order to lessen the strain of cooling requirements on mid-infrared detectors, reducing the volume of the detecting medium is one promising solution. It is necessary to augment the absorption (quantum efficiency) lost when shrinking the detector volume. A plasmonic structure has previously been reported on top of a Quantum Well (QWIP) device to improve quantum efficiency. This structure strongly enhanced absorption, but its configuration does not allow for a detector array. Due to the proximity of the plasmonic structure to the detecting medium, bump-bonding from the front would cover the plasmonic structure, and bump-bonding from the back would not allow for any isolation of devices without breaking. To address this issue, we have developed a method based on an embedded surface-plasmonic structure.

We present a QWIP with a plasmonic structure embedded within and around the detection media. Gold surrounds a hexagonal array of cylindrical pillars etched from a stack of QWIP, forming a self-aligned plasmonic-hole array designed for 8µm wavelength with an expected field enhancement of an order of magnitude. A planar dielectric lies on top of this structure, fills in around the pillars and lies nearly flush with the top of the detector stack. With this configuration, a planar top-contact is easily made and array formation with a strong enhancement is possible.

8868-30, Session 2

Photonic and plasmonic carbon nanohybrids for advanced optoelectronics applications *(Invited Paper)*

Judy Z. Wu, The Univ. of Kansas (United States)

Carbon-based nanostructures including nanotubes (CNTs) and graphene have superior electronic, optoelectronic and mechanical properties,

which provide fresh opportunities for designs of novel devices of extraordinary performance in addition to the benefits of low cost, large abundance, and light weight. This work explores a few such examples including type-II CNT/P3HT as well as CNT/graphene heterojunction infrared detectors, aligned ZnO nanowire/graphene hybrid ultraviolet detectors, and ionic-liquid gated plasmonic nanoparticle/graphene hybrid field-effect transistors for photo-detection in a wide spectrum selected by the localized surface plasmonic resonance frequency of the nanoparticles decorated on graphene. Critical to the high performance obtained on these devices are schemes that enable manipulation of photon absorption, exciton dissociation and charge as well as phonon transport at nanoscales. Micro/nanofabrication schemes for scaling up these devices will also be in consideration in order to achieve the compatibility with Si-based readout circuits.

8868-31, Session 2

Improvement in the sensitivity of methane detection using a double fast Fourier transform-based filter

Samira A. Mahdi, Univ. of Arkansas at Little Rock (United States); Edmond W. Wilson Jr., Harding Univ. (United States); Youhua Chen, Gary T. Anderson, Univ. of Arkansas (United States)

A multi-reflection cell has been employed to increase the sensitivity of the detection of methane gas. However, as the requirements of the detection system need to work on a low frequency range, the influence of the 1/f noise will be considered. This paper deal with this problem by investing the signal processing methods using Fast Fourier Transform (FFT) results have been shown an improvements of about 75% in the methane gas readings.

8868-7, Session 3

Optimization of performance for platinum nanowires as subwavelength bolometers

Pauline Renoux, Snorri Ingvarsson, Univ. of Iceland (Iceland); Dorine Charpentier, Institut National des Sciences Appliquées de Toulouse (France)

We fabricated nanoscale bolometers made of platinum wires framed by four contact pads, using e-beam lithography and metal deposition on SiO_2/Si wafers. The thin-film platinum wires have a width of 300 nm and a length of 1 µm. By illuminating the bolometers with light from a ceramic blackbody infrared source (1060 K, peak wavelength at 2.8 µm), we monitor the change in resistance in the structures depending on bias current. The relationship between resistance and temperature is given by : R=R_0 (1+??T)

Where R_0 is a constant and ? is the temperature coefficient of resistance (TCR) of platinum (0.002/K). With this simple equation we are able to characterize accurately the temperature change in the bolometers. From this data we extract two figures of merit for our devices, the responsivity R [V/W] and the detectivity D* [cmHz^{1/2}/W].

In previous works we studied the influence on performance of physical and operating parameters such as oxide thickness, bolometer dimensions or drive current. Lately we have been studying the role of platinum thickness on performance. Samples with a metallic sensing core of thickness between 10 nm and 80 nm were fabricated and characterized. Responsivity increased linearly as the thickness of the film was reduced. Eventually, the responsivity had increased by a factor of 3 for the thinnest sample compared to the thickest one, reaching 3.7x10^4 V/W. However, detectivity stays constant around 2x10^9 cmHz^{1/2}/W. The response time, according to our numerical estimations, of such bolometers is also reduced by a factor of 10 with the thickness decreasing, reaching a minimum value of 0.4 ns.

8868-9, Session 3

Research on multi-alkali cathode photoemission mechanism

Xiaofeng Li, Qian Guo, Qiang Lu, North Night Vision Technology Co., Ltd. (China)

In this paper, the spectral response and fluorescence spectrum of three Na2KSb multi-alkali cathodes without Cs activation, with Cs activation and with both Cs and Cs-Sb activation were measured. The measurement results show that, Na2KSb cathode after Cs activation, the cathode sensitivity was increased, long-wavelength cutoff wavelength was also increased, but the peak wavelength and peak intensity of fluorescence spectrum was essentially unchanged. The increase of long-wavelength cutoff wavelength shows that work function of cathode is reduced, so the Na2KSb cathode after Cs activation, the increase of cathode sensitivity and long-wavelength cutoff wavelength is due to the lower work function. Na2KSb cathode after both Cs activation and Cs-Sb activation, the cathode sensitivity and long-wavelength cutoff wavelength were further increased more substantial, but the peak wavelength and peak intensity of fluorescence spectrum was changed. The peak wavelength was shifted towards the short wavelength and peak fluorescence intensity was increased. The shift of peak wavelength toward short direction showed that energy level of transition electron was increased and increasing of peak intensity of fluorescence spectrum showed that number of transition electron was increased. For Na2KSb cathode with Cs activation and Cs-Sb activation, the increase of transition electrons number and transition electron energy level has a positive effect on the cathode sensitivity. Therefore the reasons of increase for cathode sensitivity and long-wavelength cutoff wavelength of Na2KSb cathode by Cs activation and Cs-Sb activation are the increase in the number of transitions and transition electron energy levels except for surface work function is reduced. Cathode surface electron escape mechanism is not yet conclusive, thus to improve the cathode sensitivity, further research is needed to figure out the objective law of cathode surface activation process. This will help to provide theoretical guidance to further improve cathode production process and to increase cathode sensitivity.

8868-10, Session 3

A measurement of the dielectric, conductance, and pyroelectric properties of MWCNT:PVDF nanocomposite thin films for application in infrared technologies

Matthew E. Edwards, John C. Corda, Michael J. Curley, Manmohan D. Aggarwal, Alabama A&M Univ. (United States)

In this work, we have determined the dielectric and conductance properties of multi-wall carbon nano-tubes (MWCNT) in poly vinylidene fluoride (PVDF) thin film composites as a function of temperature and frequency. The samples, ~ 24 microns in thickness, were measured in a temperature range from 40 to 60 0C and frequencies from 40 Hz to 10 MHz. Our samples were prepared by using the solution casting technique. These measures indicate that at constant temperatures, the real dielectric constant decreases at lower frequencies but rise at higher frequencies. The dielectric loss property, being a particular concern as it is directly proportional to the conductance, also decreases at lower frequencies but rise at higher frequencies with a steeper slope in each case. Additionally, we have measured pyroelectric coefficient in the same temperature range, compared the pyroelectric results with previous measures made on silver nanoparticle in PVDF thin films, and provided preliminary evidence of the causative microscopic mechanism. Our MWCNT:PVDF thin films yield higher figures of merit than that indicated by pure PVDT thin films. The results indicate a usage of MWCNT: PVDF thin films in infrared un-cooled sensors and vidicon technology.

8868-11, Session 3

CMOS compatible IR sensors by cytochrome c protein

Chien Jen Liao, National Taiwan Univ. (Taiwan)

Due to the progression of the semiconductor industry in recent years, the uncooled Infrared sensor, microbolometer, has opened the opportunity of achieving low cost infrared imaging systems for both military and commercial applications. Therefore, various fabrication process and different materials for microbolometers have been developed actively. The cytochrome c (protein) thin film has been reported as high temperature coefficient of resistance (TCR), which is related to the performance of microbolometer directly. The superior TCR value can improve the performance of microbolometer. In this paper, we introduced a novel fabrication process using aluminum which is compatible with the Taiwan Semiconductor Manufacture Company (TSMC) D35 2P4M process as the main structure material. These benefits the device to be integrated with readout integrated circuit (ROIC).The aluminum split structure is suspended by sacrificial layer utilizing the standard photolithography technology and chemical etching. The height and thickness of the structure are carefully considered. Besides, cytochrome c protein is ink-jetted onto the aluminum structure by using the inkjet printer with precise control. In measurement, incident Infrared radiation can be detected and later the heat can be transmitted to adjacent pads to send out the signal. The result showed that the TCR value of cytochrome c thin film exceeded 20% 1/k, ranging from room temperature to forty degrees Celsius. This approach applies an inexpensive and simple fabrication process and makes the device suitable for integration. In addition, the performance can be further improved with low noise readout circuits.

8868-25, Session 3

ZnMgO solar blind detectors: from material to systems *(Invited Paper)*

Mehdi F. Anwar, Abdiel Rivera, Anas Mazady, Hung Chi Chou, John W. Zeller, Univ. of Connecticut (United States); Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States)

We will report the growth of ZnMgO nanowires (NW) using low pressure MOCVD. Substrate dependence NW growth will be discussed. We will present the incorporation of Mg up to 30%, on Si-substrate, demonstrating excellent material characteristics as determined by SEM, XRD and PL measurements. Fabrication of detectors arrays along with UV characterization will be reported.

8868-13, Session 4

On-line nonuniformity and temperature compensation of uncooled IRFPAs using embedded digital hardware

Alejandro Wolf, Rodolfo Redlich, Jorge E. Pezoa Nunez, Miguel E. Figueroa, Univ. de Concepción (Chile)

We present a model and a signal-processing scheme for compensating the nonuniformity noise and surrounding temperature self-heating effects on the response of uncooled microbolometer-based infrared cameras. The model for the nonuniformity considers pixelwise gain and offset parameters. The representation for the self-heating dynamics of the camera is an autoregressive moving-average (ARMA) model for camera's internal temperature. The scheme performs initially a two-point calibration at a known surrounding temperature. Next, without modifying the nonuniformity parameters, we dynamically compensate variations in the camera readout using both estimates of the ARMA model and measurements of the surrounding temperature taken by a simple sensor embedded in the camera. Tested on a CEDIP Jade UC33 camera, our system compensates reference black-body images with an error below 0.54 degrees Celsius in scenarios where the room temperature varied up to 14 degrees Celsius. Moreover, the regularity and simplicity of the algorithm enables us to implement it on embedded digital hardware, thereby reducing its cost, size, and power consumption. We implemented the algorithm on a Xilinx XC6SLX45 FPGA using fixed-point arithmetic. The circuit exhibits an arithmetic error of 0.06 degrees compared to a software double-precision implementation. It compensates 320x240-pixel video at up to 1,437 fps and 640x480-pixel video at up to 360 fps, using 1% of the logic resources of the FPGA, and less than 1 mW of dynamic power at 110 MHz. Adding Gigabit Ethernet communication, HDMI display, and a pseudocolor map on the chip uses only 10% of the resources and consumes in total 915 mW.

8868-14, Session 4

Radiation hardness by design for mixed signal infrared readout circuit applications

James Gates, Stephen D. Gaalema, Greg Pauls, Dave Dobyns, Bruce Wall, Black Forest Engineering (United States)

Readout integrated circuits (ROICs) to support space-based infrared detection applications often have severe radiation tolerance requirements.

Radiation hardness-by-design (RHBD) significantly enhances the radiation tolerance of commercially available CMOS and custom radiation hardened fabrication techniques are not required. The combination of application specific design techniques, enclosed gate architecture nFETs and intrinsic thin oxide radiation hardness of 180 nm process node commercial CMOS allows realization of high performance mixed signal circuits. Black Forest Engineering has used RHBD techniques to develop ROICs with integrated A/D conversion that operate over a wide range of temperatures (40K-300K) to support infrared detection. ROIC radiation tolerance capability for 256x256 LWIR area arrays and 1x128 thermopile linear arrays is presented. The use of 130 nm CMOS for future ROIC RHBD applications is discussed.

8868-15, Session 4

Wavelength stabilization of electrostatically actuated micromechanical infrared Fabry-Pérot filters

Jörg R. Schröter, Sebastian Lehmann, Martin Ebermann, Norbert Neumann, InfraTec GmbH (Germany)

It is well known that many gases, fluids and solids yield material specific absorption spectra within the infrared range. Tunable MEMS Fabry-Pérot filters (µFPF) can be applied in miniature sensors, which identify certain substances that are optically active in mid-wavelength infrared. Researchers focus on improving accuracy, sensitivity and robustness of such sensors in order to enable their usage in rough environments as well as in portable devices..

We use bulk micro-machined µFPF with Bragg-reflectors deposited on thick carriers, one fixed and the other suspended by springs. It is actuated electrostatically to tune the reflector distance and hence the filter wavelength. Compared to surface micro-machined devices, this design opens path to higher optical performance due to high parallelism of substrates, but introduces the drawback of acceleration sensitivity because of a moving mass.

To overcome this problem, the filter is driven by a closed-loop control, wherein position feedback is given by an ASIC that directly measures the actuator capacitance, without the need of area-consuming sensing electrodes. We have developed a PI-based controller that adapts to the nonlinear stiffness and damping by recalculating the controller parameters in real-time, depending on the current position. Basic system parameters are derived from optical (FTIR) calibration and step-response measurements. The tuning range was 1300 nm in the mid-wavelength infrared with control voltages up to 35 V. At 5 Hz sinusoidal accelerations of 1 g, we improved the filter wavelength accuracy from ±35 nm in the open-loop case down to ±2 nm in closed-loop operation.

8868-16, Session 5

Split-manufacturing of safe and secure integrated circuits *(Invited Paper)*

Dennis L. Polla, Defense Advanced Research Projects Agency (United States)

No Abstract Available

8868-18, Session 5

Modelling of MG-Y laser tuning characteristics

Juraj Poliak, Brno Univ. of Technology (Czech Republic); Hilmar Heininger, Friedemann Mohr, Pforzheim Univ. (Germany); Otakar Wilfert, Brno Univ. of Technology (Czech Republic)

For many years, tuneable lasers were mainly utilized in spectroscopic applications. However, in last years they are becoming employed in other industrial applications as well, e.g. optical fibre sensors for optical remote sensing (distributed fibre optical sensing). Mechanical tuning of lasers decreases their performance, e.g. the tuning speed and the tuning repeatability. Lately, a Modulated Grating Y-branch (MG-Y) laser Syntune S7500 has been introduced using a novel and fully electronic laser tuning with combination of two individually tuned Bragg gratings and tuning of the phase difference. The tuning is carried out by means of changing three currents offering wide tuning range in the whole C band, fast-speed tuning capabilities and high-power output on a single chip.

The MG-Y laser is currently being used solely for telecommunication applications, where the wavelength is chosen from the ITU grid containing 89 channels at 50 GHz spacing by means of tuning three currents listed in a look-up table (LUT). To fully exploit the tuning properties of the device in sensor applications, the tuning step must be as small as possible. This requirement increases the size of the LUT and slowing down the tuning process.

In this paper we propose an analytical approach of describing the tuning properties of the MG-Y laser by means of analytical description of the wavelength dependence of the three tuning currents. The model is based on the theoretical analysis and it was experimentally verified. The results of experiments are included in the second part of the paper. Finally, we conclude with the discussion on the model precision and applications.

8868-19, Session 5

Mechanically induced long-period fiber gratings in Er3+ fiber for structural health monitoring

Maria G. Pulido-Navarro, José A. Alvarez-Chavez, Ctr. de Investigación e Innovación Tecnológica (Mexico); Daniel E. Ceballos-Herrera, Univ. Autónoma de Nuevo León (Mexico); Ponciano J. Escamilla-Ambrosio, SEGOB (Mexico)

This work presents preliminary results on wavelength sensitivity due to mechanically induced long period fiber grating (LPFG) on both standard single-mode and Er-doped fibers. The work presents and compares results for both types of fibers under different torsion conditions. In order to apply the torsion one of the fiber ends is fixed while torsion is performed on the other end. A LPFG whose period is 503 μm is used to press the fiber after the torsion, this will allow for micro curvatures to be formed on the fiber, which will in turn generate a periodical index perturbation on it. Here, it was noted that the rejection band shifts to longer wavelengths for Er-doped fibers. It was detected that for torsion of 6 turns applied to 10 cm doped fiber the wavelength peaks can be moved up to 25 nm, which is longer than similar results reported on standard fibers. Therefore, by using Er-doped fibers this technique will give more sensitive and accurate results on the real conditions of the structure under study. These results can be employed for sensing applications, especially for small to medium size structures, being these structures mechanicals, civil or aeronautical. Theoretical calculations and simulations are compared for experimental results validation and will be included in the presentation.

8868-26, Session 5

Heteroengineering infrared detectors with type II superlattices *(Invited Paper)*

Sanjay Krishna, The Univ. of New Mexico (United States)

Type II superlattices in the InAs/GaSb system provide a lot of band engineering flexibility. A wide variety of unipolar barriers have been investigated in this material system. In this talk, I will review some of our work on unipolar devices and review the fundamental limiting mechanisms for these detectors.

8868-27, Session 5

Development of large-area nanostructured AR coating for EO/IR sensor applications

Ashok K. Sood, Roger E. Welser, Gopal G. Pethuraja, Magnolia Optical Technologies, Inc. (United States); Nibir K. Dhar, Dennis L. Polla, Defense Advanced Research Projects Agency (United States); Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

No Abstract Available

8868-29, Session 5

MWIR type-II InAs/GaSb superllatice cascade photodetectors *(Invited Paper)*

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Recently, a new strategies used to achieve high operation temperature (HOT) detectors include barrier structures such as nBn, material improvement to lower generation-recombination leakage mechanisms, alternate materials such as superlattices and cascade infrared devices. Another method to reduce detector's dark current is reducing volume of detector material via a concept of photon trapping detector.

In this paper, the performance of a novel HOT detector designs, so called interband cascade type-II MWIR InAs/GaSb superlattice detectors, is presented. Detailed analysis of the detector's performance (such as dark current, RA product, current responsivity, and response time) versus bias voltage and operating temperatures (220 – 400 K) are performed pointing out optimal working conditions. At present stage of technology, the experimentally measured R0A values of interband cascade type-II superlattice detectors at room temperature are higher than those predicted for HgCdTe photodiodes.

8868-21, Session 6

Evolution of EO/IR technology and systems *(Invited Paper)*

Keith L. Lewis, Sciovis Ltd. (United Kingdom)

No Abstract Available

8868-22, Session 6

Multiscale modeling of photon detectors from the infrared to the ultraviolet *(Invited Paper)*

Enrico Bellotti, The Boston Univ. Photonics Ctr. (United States)

Due to the ever increasing complexity of novel semiconductor systems, it is essential to possess design tools and simulation strategies that include in the macroscopic device models the details of the microscopic physics and their dependence on the macroscopic (continuum) variables. Towards this end, we have developed robust multi-scale modeling capabilities that begin with modeling the intrinsic semiconductor properties. Using techniques such as the empirical pseudopotential method or density functional theory we calculate the band structures of semiconductor alloys and their constituent binary compounds. Then, using the Monte Carlo method we analyze characteristics such as the high field carrier transport, radiative recombination and Auger recombination rates. The models are fully capable of incorporating effects of substrate driven stress/strain and the material quality (dislocations and defects) on microscopic quantities such as the local transport coefficients and non-radiative recombination rate. We then use the microscopic material parameters as an input into device simulations. Using a finite-difference time-domain (FDTD) approach we have analyzed the electromagnetic response of semiconductor devices, computed the carrier generation rate in the device and evaluated the reflectance. We then use the finite element method (FEM) to perform drift-diffusion simulations which use the optical generation rate from the FDTD simulations as an input. In the FEM simulations we simultaneously solve the carrier continuity and Poisson equations on a three-dimensional finite element grid to compute the photo-current and subsequently the quantum efficiency and modulation transfer function. Using this modeling approach we have extensively studied infrared focal plane arrays. Particular emphasis was placed on HgCdTe and InAsSb arrays incorporating photon trapping structures as well as two-color HgCdTe detectors arrays.

8868-23, Session 6

Unleashing giant TCR from phase changes in carbon nanotube composites for EO/IR sensor applications *(Invited Paper)*

Gustavo E. Fernandes, Jin Ho Kim, Jimmy Xu, Brown Univ. (United States); Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States)

We review our recent work on carbon nanotube-polymer nanocomposites with a phase-change polymer. This nanocomposite is found to achieve very large temperature coefficient of resistance (TCR), ≈? 10%/ ° C, which is about one order of magnitude larger than the TCR observed in other carbon nanotube materials to date. The giant TCR results from a volume-phase-transition that directly changes the tunneling resistances that electrons experience in moving between nearby carbon nanotubes. We studied the bolometric photoresponses of this new material and found that the bolometric figures of merit, namely the responsivity and time constant, are also strongly affected by the phase transition. The nanocomposite's enhanced responses to temperature and humidity give it strong potential for sensor applications and uncooled infrared detection.

8868-28, Session 6

Development of GaN UVAPD for ultraviolet sensor applications

Ashok K. Sood, Robert A. Richwine, Roger E. Welser, Magnolia Optical Technologies, Inc. (United States); Nibir K. Dhar, Defense Advanced Research Projects Agency (United States); Russell D. Dupuis, Georgia Institute of Technology (United States)

No Abstract Available

8869-12, Session PMon

Evapotranspiration analysis based on topography algorithm in the Yellow River Delta

Jicai Ning, Zhiqiang Gao, Yantai Institute of Coastal Zone Research (China); Wei Gao, USDA UV-B Monitoring and Research Program, Natural Resource Ecology Laboratory, CSU (United States)

Remote sensing provides an approach to monitor land surface energy and water balance on regional scale simultaneously, which is very important and useful in researches and applications in global climate change, hydrology, ecology and agriculture etc. Evapotranspiration (ET) may be used as an ecological indicator to address the ecosystem complexity. The accurate measurement of ET is of great significance for studying environmental sustainability, global climate changes, and biodiversity. Remote sensing technologies are capable of monitoring both energy and water fluxes on the surface of the Earth. With this advancement, existing models, such as SEBAL, S SEBI and SEBS, enable us to estimate the regional ET with limited temporal and spatial coverage in the study areas. Exchanges of materials and energy flows were more complex in the Yellow River Delta with the interaction between the land and the ocean. Based on the widely and successfully applied SEBAL model, topography correction (slope, aspect and elevation) for some model parameters, automatically detection the dry and wet pixels and effectively simulated the evapotranspiration (ET) of the water body have been done to establish the regional ET remote sensing model in the context of digital elevation model (DEM), expanding the application of the regional ET remote sensing model. Taking into account the terrain factors, we modified the algorithm of SEBAL model . Results showed that, the modified inversion method of evapotranspiration can better reflect actual evapotranspiration condition. Evapotranspiration changes were consistent with climate and land use change through a multi-phase inversion results.

8869-13, Session PMon

Monitoring on urbanization of Shanghai in recent fifteen years based on remote sensing

Chong You, East China Normal Univ. (China)

Since 1995,“the land use/land cover change”study plan was internationally put forward,it has become one of the hot topics in global studies.Shanghai is China’s largest city and economic center.For 15 years,it has been through the reform of socialist market economy,Pudong development,population expansion and city building boom.Therefore,the study Shanghai region’s land use change has important sense.
Based on the interpretation of remote sensing data and GIS software support,using Shanghai 1990,2000 and 2005 three issue of interpretation of remote sensing data,I has been working on Shanghai city’s nearest 15 years land use/land cover information extraction and statistical analysis.Methods are including city expansion intensity index,buffer analysis and spatial variation analysis.And I studied Shanghai city land use change rule in recent 15 years,city land spatial pattern change and its driving force. Through the study,the main conclusions are: (1) Shanghai’s urbanized increased from 10.77% in 1990 to 32.96% in 2005,increased 22.19% in total.The main performance is the increase of city construction land,industrial land and traffic land.Among them,the growth rate from 1990 to 2005 is 0.43% and the growth rate from 2000 to 2005 is 1.99%;(2)From the buffer analysis,urbanized area mainly concentrated in the city center district within 12km in 1990,and farmland mainly concentrated out of 12km;In 2000,urbanized area extend to the scope of the 20km;And in 2005,urban land extend to the scope of the 40km,And appeared a peak in the 60km.It shows that the urbanized area of Shanghai is increasing year by year; (3)Spatial growth direction characteristics:in the past 15 years in Shanghai’s urbanized area in different orientations of the expansion differed.Overall, from 1990 to 2005,Shanghai city urbanized area mainly extended to the northeast,Southeast and southwest.(4)Human driving factors such as the economic factors,demographic factors and technical factors and other factors drive significantly on Shanghai city urbanized area change.

8869-15, Session PMon

Analysis trends of ultraviolet B fluxes in the continental US with USDA and TOMS data

Zhiqiang Gao, Institute of Geographical Sciences and Natural Resources Research (China); Wei Gao, Colorado State Univ. (United States)

Many environmental factors, such as stratospheric ozone, aerosols, and clouds, may affect ultraviolet (UV) irradiance. The aim of this study is to investigate the possible association between ultraviolet B (UVB) radiation and total cloud amount, ozone, and aerosols simultaneously, leading to the assessment of possible impacts of climate change on UVB flux variations in the Continental United States (US). Spatiotemporal correlation analyses are conducted based on data collected from the Total Ozone Mapping Spectrometer (TOMS) and the International Satellite Cloud Climatology Project (ISCCP) with a geographic information system (GIS).

8869-16, Session PMon

Concomitant flow and space variations of evapotranspiration due to changes in LUCC under seawater intrusion in a coastal region

Zhiqiang Gao, Xiaoming Cao, Institute of Geographical Sciences and Natural Resources Research (China); Wei Gao, Colorado State Univ. (United States)

This paper will provides a coherent pattern identification analysis of coastal land use and land cover (LULC) under the impact of seawater intrusion. This study analysis applied the 4-, 3-, and 2-band false color composite Landsat satellite data to characterize the LULC in the study area. The evapotranspiration (ET) and heat fluxes will be estimated by using the SEBAL model with two-time phase thermal infrared band images and regional surface parameters. This will allow for the eventual linkage of seawater intrusion to land use and land cover change (LUCC) and ET variations over time. The spatial distribution pattern and change characteristics of ET will be formed by double driving forces of seawater intrusion and LUCC under the background effects of regional climate.

Keywords: Evapotranspiration, Land use and land cover, Remote sensing, Seawater intrusion.

8869-17, Session PMon

Assessment of ozone pollution monitoring based on improved regional assimilation meteorology field in the WRF-Chem model

Yan-an Liu, Chaoshun Liu, Wei Gao, Runhe Shi, East China Normal Univ. (China)

Air quality has become a social issue concerned by publics, especially in Shanghai, a city with rapid economic development. The research uses the improved meteorology field provided by regional assimilation system

as the input field of WRF-Chem model, and then compares the forecast ozone data with the observations. The results show that the relationship between the forecast ozone concentration and observations is consistent in whole, and the forecast at 24h is better, but gradually decreases with the increase of forecast time?the model has an outstanding ability on the strong ozone day forecast; the prediction error of ozone also has a high relation with the simulation accuracy of model precipitation; the improved meteorology field obviously reduces the errors of ozone forecast. Therefore, the ozone forecast based on the improved regional meteorology field at the WRF-Chem model will not only provide decision-making data for the sake of building a green city, but also plays an important instructional role in controlling the air pollution and urban smog.

8869-18, Session PMon

Interpolation of XCO2 retrieved from GOSAT in China using fixed rank kriging

Cong Zhou, Runhe Shi, East China Normal Univ. (China)

Greenhouse Gases Observing Satellite (GOSAT) can provide high accuracy column-average dry air mole fractions (XCO2), however, the observations also have large gaps because of the impact by cloud and the observational mode. Kriging interpolation yeilds best linear unbiased predictor, it will be a computational work if the dataset is large. Fixed Rank Kriging (FRK) is based on the Spatial Random Effect (SRE) model, which assumes that the process of interest can be expressed as a linear combi-nation of spatial basis functions, plus a fine-scale-variation component. FRK predictors and standard errors can be computed rapidly. This paper analyzed the FRK prediction of GOSAT Level2 XCO2 data over China. The result shows that FRK prediction is cocurrent with other Kriging methods (e.g. Ordinary Kriging). In addition, the result agrees well with the station measurements at Mt. Waliguan and Shangdianzi.

8869-19, Session PMon

Typhoon observations from multiple satellite imagery

Jingsong Yang, The Second Institute of Oceanography, SOA (China)

MTSAT (Multi-functional Transport SATellite), FY-2 (Fengyun, Chinese meteorological satellite) and EOS MODIS (MODerate-resolution Imaging Spectroradiometer) optical imagery and Envisat ASAR (Advanced Synthetic Aperture Radar) imagery were used to analyze the typhoons in the Western North Pacific from 2005 to 2011. While MTSAT, FY-2 and MODIS observe the cloud-top of typhoons, SAR observes the footprints of typhoons on the sea surface by penetrating the clouds. Several cases of typhoons are used to compare the typhoon eyes observed by SAR (on the sea surface) with optical (on the cloud top) images. Typhoon eyes were retrieved by using wavelet analysis. Furthermore, the best track data from the Joint Typhoon Warning Center (JTWC), Chinese Meteorological Administration (CMA), and the Japan Meteorological Agency (JMA) are used for the calibration and validation. Large horizontal distance between typhoon eyes on the ocean surface and on the cloud top is found.

8869-20, Session PMon

Research review on observing atmospheric aerosols optical depth by means of multifilter rotating shadowband radiomete

Man Yi Wang, East China Normal Univ. (China)

Atmospheric aerosols play an important role in the transmission of the solar radiation and formation of atmospheric haze,so that the research of aerosol became a focus point. Multifilter rotating shadowband radiometer (MFRSR) has gradually become a more and more widely tool to observe atmospheric aerosols optical depth in the world. It uses automated rotating shadowband technique and excellent diffuse scattering detector to alternatively measure total horizontal and diffuse horizontal irradiances at seven wavelengths simultaneously, and then deduce direct normal irradiance. In this paper, the instrumentation, the different methods of calibration and data processing are introduced. And we also compare the results of MFRSR and AERONET data in order to illuminate the reliability of observed aerosol optical depth with MFRSR. In addition, the reasons of possible error are analysised, and the trend of observing aerosols optical depth by means of MFRSR is discussed.

8869-21, Session PMon

Analyzing the nonstationary space relationship of city greenness degree and social economic conditions in Shanghai, China using OLS and GWR models

Kejing Wang, Yuan Zhang, Youzhi An, Zhuoxin Jing, East China Normal Univ. (China); Wei Gao, East China Normal Univ. (China) and Colorado State Univ. (United States)

The purpose of this research is to explore the non-stationary relationship between socio-economic conditions and greenness across shanghai ,China, using Ordinary Least Squares (OLS) and geographically weighted regression (GWR). The analysis integrates environmental data on vegetation cover, using Normalized Difference Vegetation Index (NDVI) values derived from 2003 Shanghai MODIS imagery to reflect the city green degree level, conducted at the census block group level for shanghai. To explore regional variations in the relationship, City-wide OLS and local GWR models are developed by regressing mean NDVI against three independent variables generated by regressing each of the following socio-economic variables –urban land use, GDP and population density . Research shows that a considerable distinctive spatial variation exists in the relationship for each model and these models indicate that the strength and character of the relationship among the variables varies spatially. Results also indicates that GWR model has superior effect and higher precision than the OLS model at the scale of census block group and should be used for regional scale spatial analysis to account for local effects and geographical variation. From the paper we can see that while urban land use and population density are the impact factors of negative inflience of vegetation vigor in some neighborhoods in shanghai, this relationship changes drastically across the big important chinese city environment.

8869-22, Session PMon

Application of genetic algorithm in atmospheric carbon dioxide concentration retrieval

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This paper introduced the basic theory and methods of CO2 retrieval whose key step is to search for the optimal solution. Genetic Algorithm is an efficient random search algorithm, which can avoid the local optimization effectively. In this paper, the basic principles of Genetic Algorithm in CO2 retrieval were investigated and the corresponding encoding and decoding method and the fitness function were designed. The Genetic Algorithm is then applied to retrieve atmospheric CO2 concentration from a three years AIRS observations dataset. The retrieval results agreed well with the aircraft measurements with 1.13ppmv RMS errors and clear season cycles.

8869-23, Session PMon

The differences analysis of UHI character between air temperature and LST

Ke Liu, Xingfa Gu, Institute of Remote Sensing and Digital Earth (China); Wei Gao, East China Normal Univ. (China); Zhiqiang Gao, Institute of Geographical Sciences and Natural Resources Research (China)

Though LST (Land Surface Temperature) show some similar spatial and temporal patterns to UHI (Urban Heat Island) effect for air temperatures, there were significant differences. This paper was based on the 2006 Landsat TM remote sensing images, the 2006 general weather information?include air temperature, precipitation, atmospheric pressure, sunshine and wind power ?of 10 Shanghai meteorological stations four times per day (02:00, 08:00, 14:00, 20:00 (UHT+8)), and the 2006 MODIS LST data of Shanghai region at the nearly same time (01:30, 10:30, 13:30, 22:30 (UHT+8)). First, a 2006 land cover classification of the Shanghai region was derived using Landsat TM image. Second, under calm, clear weather conditions, Contrast and analysis of UHI of air temperatures and LST had been studied, included the analysis of the general characteristics of UHI based on LST and air temperature, the time of day and season of maximum UHI development, the relationship between land use and UHI intensity, the spatial UHI intensity variability by day and season. And in the end, we studied the possible reasons of the relationship between these differences and satellite sensor, observation time, land cover of underlying surface of meteorological stations, and near _surface heat fluxes.

8869-24, Session PMon

Relationships between urban heat island effect and land use around weather stations

Ke Liu, Institute of Remote Sensing and Digital Earth (China); Wei Gao, East China Normal Univ. (China); Xingfa Gu, Institute of Remote Sensing and Digital Earth (China); Zhiqiang Gao, Institute of Geographical Sciences and Natural Resources Research (China)

Based on the relationship between various underlying surfaces intercepted from the different-radius circular buffer zones (the radius is respectively 1, 2, 4, 8km, with 10 Shanghai weather stations as their center) and their corresponding air temperatures (four times per day , 0200, 0800, 1400, 2000(LST)). It is found that a strong positive correlation between construction land and UHI, and a negative correlation between woodland/grassland and UHI. There is a relatively strong positive correlation between water bodies and UHI at night. The influence of different types of underlying surfaces on UHI varies with different hours every day. As far as range of influence is concerned, construction land is within 6 km, woodland/grassland is within 4 km, farmland influence reaches its peak at 4 km, influence of water body is uncertain. At last, it is mainly discussed the possible reasons for how the correlation between different underlying surfaces and UHI can be formed. And based on land use around weather Stations and the population data of town (should be county/district in china), it is discussed the conditions surrounding the normal rural station from which urban effects are to be calculated.

8869-25, Session PMon

A simple estimation model of aerosol optical thickness based on meteorological station observed atmospheric visibility

Zhu Li, Jianyu Chen, The Second Institute of Oceanography, SOA (China)

Aerosol optical thickness(AOT) and atmospheric visibility are two important weather parameters. AOT reflects the state of the atmosphere and atmospheric visibility is widely used in various aspects of social life. Generally, it is reported in literatures that both of them are effected by Air Pollutants and other meteorological factors, such as surface pressure, ground temperature, wind speed, precipitation. In this paper, a statistic relationship expression is established between AOT and atmospheric visibility on the basis of the point-to-point meteorological observations. Based on observed data provided by the main national meteorological stations throughout China, the relevant analysis has been carried out between the Air Pollution Index(API) and the sunphotometer aerosol optical thickness. In the national region, the correlation between atmospheric visibility and weather factors indicates that the surface pressure has great influence on atmospheric visibility all the year round. And the influence based on precipitation is more obvious in spring and summer, meanwhile wind speed and temperature play important roles in autumn and winter. A significant positive correlation was found between AOT and API. To express the relationship between atmospheric visibility and AOT, some computable models were utilized, including linear function, logarithmic function, cubic curve, power function, inverse function and so on. According to the accuracy analysis, the cubic curve model and the power function model are more accurate. And both R Square of them is higher than 0.47. But the coefficient of cubic curve is more complex in practice. Finally, a simple estimation model of aerosol optical thickness based on meteorological station observed atmospheric visibility was conducted using power function. The Pearson coefficient between calculation of power function and observation is 0.73.

8869-26, Session PMon

Effect of nitrogen stress on relationship of PRI and LUE during winter wheat growth period

Jianmao Guo, Nanjing Univ. of Information Science & Technology (China)

Light use efficiency (Light-Use Efficiency, LUE) is an important parameter for GPP and and NPP estimation model, cause by the existing model method to estimate the actual LUE is always simple and rough, which may lead to serious bias by GPP and NPP. The photochemical reflectance index (Photochemical remote sensing Reflectance Index, PRI) has great potential for direct estimation the actual LUE. In this paper, wheat in different nitrogen treatments was designed in field trial during Wheat growing period, for obtain photosynthesis and reflective hyperspectral data, and then LUE and PRI was calculated in critical period of wheat growth. The results show that, at different growth stages under three different nitrogen conditions, LUE and PRI value were significantly increased with increasing nitrogen absorption; Last longer, more capable of absorbing nitrogen amount, the correlation between LUE and PRI was better?for example, the correlation coefficient is obviously larger in heading stage than elongation stage for same nitrogen treatment.

8869-27, Session PMon

Absorption coefficient of CDOM in Zhejiang coastal waters

Guannan Fan, Zhihua Mao, Peng Chen, Haiqing Huang, The Second Institute of Oceanography, SOA (China)

Chromophoric dissolved organic matter (CDOM) exists in all natural waters. Researches on optical properties of CDOM play an important role in ocean color remote sensing retrieval. The optical properties of CDOM in Zhejiang coastal waters were investigated from August 18 ,2009 to June 9 ,2011 covering four seasons. In this paper, CDOM light absorption parameters were researched in Zhejiang province and its adjacent waters to achieve the following objectives: 1) According to CDOM absorption coefficients measurement data of this voyage, the geographical

distribution and its influencing factors of the absorption coefficient values of CDOM were explored; 2)The relations of CDOM absorption values and salinity have been used to reaserch the of mixing behavior of CDOM to explore the behavior of CDOM mixing process of the study area. Based on the measured data, the distribution of the absorption coefficient of CDOM was analyzed. The results showed that absorption coefficient at 440 nm (a(440)) decreased with the offshore direction, and the relatively high value of a(440) was observed generally in the coastal waters and low value in the adjacent waters.The distribution reflected the terrigenous origin characteristics of CDOM .The relationship between salinity and a(440) of the four seasons was discussed. The results demonstrated that a(440) had a significant negative linear relationship with the salinity.That is to say,CDOM took on the conservative behavior in the research region.

8869-28, Session PMon

A new algorithm based on spectral differences for red tide monitoring in the East China Sea

Xiaohui Xu, South China Sea Institute of Oceanology (China) and Graduate Univ. of the Chinese Academy of Sciences (China); Delu Pan, Zhihua Mao, Bangyi Tao, The Second Institute of Oceanography, SOA (China)

Red tide is an ecological anomaly phenomenon in which phytoplankton, protozoa or bacteria in seawater suddenly proliferate or aggregate under certain environmental conditions and within a period of time, resulting in seawater discoloration. Red tide not only destroys marine fishery production, deteriorates the marine environment but also causes human health problems. In China, the East China Sea has a high incidence of red tide disasters; both the frequency and area of red tides are significantly higher than in other regions. Remote sensing technology has been proven the most effective means of monitoring red tides. Red tide organisms accumulate and cause the water color change, which alters the water spectral characteristics that can be detected by remote sensing. Spectral information of red tide water is therefore an important basis for establishing red tide remote sensing monitoring models. This paper analyzes and compares differences in red tide event spectral curves and multiyear monthly averaged spectral curves, and develops a red tide monitoring algorithm based on the background field, to extract red tide information of the East China Sea. This algorithm is applied to red tide events in that sea, find that the algorithm can effectively determine the location of red tide, with good correspondence to results from an official bulletin. This demonstrates that the algorithm can effectively extract red tide information.

8869-29, Session PMon

Inversion of water quality parameters in the Hangzhou bay based on the high-resolution satellite HJ-1A/B imagery

Qinghui Meng, Zhihua Mao, Haiqing Huang, Yuzhang Shen, The Second Institute of Oceanography, SOA (China)

HJ-1A/B were two small satellite constellations, that were launched for the environment and disaster monitoring and forecasting on September 6th, 2008. This paper focused on the inversion method of water quality parameters in the dynamic water bodies of the Hangzhou bay with HJ-1A/B satellite imagery. First, the atmospheric correction of HJ-1 A/B CCD imagery was carried out using fast line-of-sight atmospheric analysis of spectral hypercubes (FLAASH) model, in which aerosol optical depth was retrieved from synchronous MODIS-Terra data. Then, the inversion of water quality parameters were performed based on the classical band ratio algorithms, which have been modified in order to be applied to the inversion of the case 2 water. The retrieval algorithm for total suspended particle matter was based on the classical red/green band ratio algorithm and corrected with an exponential term which would give a better result on high suspended matter concentration area. For the chlorophyll-a concentration retrieval algorithm, the blue/green band ratio algorithm is also corrected for the influence of non-pigmented particle to give feasible outcome for the TSM dominated area. As for the Secchi Disk Depth, two band reflectance ratio exponent method is applied. To verify the inversion result, the synchronized in situ data were used. The mean relative errors of the retrieved water quality parameters are less than 40%. Results reveal that the inversion accuracy of water quality parameters in case 2 water can be improved with using HJ-1A / B satellite imagery.

8869-30, Session PMon

Retrieving rice yield and biomass from Radarsat-2 SAR data with artificial neural network (ANN)

Zhuoxin Jing, Yuan Zhang, East China Normal Univ. (China)

Abstract?Estimating crop yield using remote sensing is a key research and application field in agricultural remote sensing. A practical scheme for estimating rice yield from Radarsat-2 data is presented, which demonstrates that Radarsat-2 data can be an important data source for monitoring rice system and estimating rice yield. Artificial neural network (ANN) method was provided for rice yield estimation based on the relationship between the backscattering coefficients of Radarsat-2 data and rice parameters. The rice backscattering coefficients were extracted from multi-temporal Radarsat-2 images, which were combined with the observed rice parameters at field in Aug. 21 (heading stage) and Sept. 14 (maturing stage) to establish the optimal ANN. The rice yield and biomass in Aug. 21 and Sept.14 were retrieved based on the trained network, respectively. And the spatial distribution maps of rice yield and biomass were produced for each rice pixel. By comparing the retrieved results and the measured data, it showed that rice yield and biomass in Aug. 21 and Sept.14 errors were estimated with the root mean square error (RMSE) at approximate 147.09g/m2?170.49 g/m2?226.03 g/m2, respectively. The result indicates that integration of Radarsat-2 data and ANN method can be applied to efficiently estimate rice yield and biomass with acceptable accuracy.

8869-31, Session PMon

Extracting desertification in Mongolian Plateau based on NDVI-Ts space

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Combining the spectral vegetation index with thermal infrared information, the triangular space of NDVI-Ts based on satellite remote sensing data provides and effective method for monitoring. Vegetation-Temperature Condition Index (VTCI) based on the triangular space of MODIS NDVI-Ts is applied to monitoring desertification in Mongolian Plateau from 1990 to 2010. The VTCI is based on satellite derived information only, and therefore the index is potential for operational application. It's found that the space of NDVI-Ts for the whole study area is typically triangular because the monitored area is large enough to make the value of NDVI and soil moisture vary in a very large scope. Then, a linear regression analysis is conducted to get the equations of the dry and wet line from the triangular space for the whole area, and the VTCI for the Mongolian Plateau is extracted. Combined with MODIS land cover product IGBP and frequency distribution of the VTCI, the spatial pattern and temporal evolution of the drought are also analyzed. At last, the ground-measured precipitation data at the same periods are used to validate the drought monitoring measurements.

The results show that the drought widely distributed in spatial scale and is very serious. It is more serious in Mongolia than that in inner-Mongolia. In different periods, there would be some differences between Mongolia and inner-Mongolia. The correlation analysis between VTCI and ground-based measured precipitation indicates that there is a signification linear

correlation between VTCI and total monthly precipitation. The VTCI and cumulative total monthly precipitation are also linearly correlated from the monitoring month to the previous months. Obvious correlation is also found between VTCI and the cumulative percentage of departure from normal monthly precipitation from the monitoring month to the previous months.

8869-32, Session PMon

Deriving leaf chlorophyll content of green-leafy desert plant (Haloxylon ammodendron) from hyperspectral reflectance

Xiaoming Cao, Institute of Geographical Sciences and Natural Resources Research (China); Zhiqiang Gao, Yantai Institute of Coastal Zone Research (China); Juanle Wang, Institute of Geographical Sciences and Natural Resources Research (China); Xi Chen, Anming Bao, Xinjang Institute of Ecology and Geography (China)

Many fundamental ecosystem properties and dynamics are monitored by plant water status, particularly in arid ecosystem where water is usually limiting. Although plant water status have been widely assessed using field measurements by ecological methods, approaches for remotely sensing plant water status are largely lacking, particularly diurnal water status. In arid ecosystem, water use efficiency (WUE) is likely to be a target of natural selection. WUE is not only an indicator of diurnal and dynamic water status, but also the integrated index of including photosynthesis and transpiration procession. In our study, the experiments were conducted on native dominant desert shrub, Haloxylon ammodendron, in their original habitats on the southern periphery of Gurbantonggut desert, Central Asia. We explored simple and useful spectral indices for estimating diurnal WUE at a leaf scale based on diurnal measurements of spectral reflectance, photosynthesis and micrometeorological variables. According to the statistical analysis of relationships between spectral indices and WUE estimation, SR type index (R2 = 0.60, P<0.000) is the sensitivity index for WUE estimation. Our results provide useful insights for monitoring desert shrubs diurnal and dynamic water status, using a wide range of available spectral data. Further research is extending leaf scale to a large scale for arid ecosystem observations.

8869-33, Session PMon

The research on the fairness of carbon emissions for Chinese energy based on GIS

Qiuxian Wang, Zhiqiang Gao, Jicai Ning, Yantai Institute of Coastal Zone Research (China)

Mainly using carbon emission inventories of 2006 IPCC, carbon emissions of China's 30 provinces in 2000-2010 are calculated on base of China energy statistical yearbook and China cement Yearbook. The figure of carbon emission showed that there are huge differences between the 30 provinces of China. But the whole trends of the total emission are increasing with the development of the economy. Then according to this result the carbon intensity in China in recent ten years and per capita carbon emissions were made. The result showed that national carbon intensity presented a decreasing trend, and the unit GDP energy consumption was also in a decreasing trend. But there are still some areas with high carbon intensity, mainly in Shanxi, Guizhou, Ningxia, Inner Mongolia and Gansu Province. While the intensity of carbon emission in such provinces with developed economic as Fujian, Guangdong, Beijing, Jiangsu, Zhejiang, Shanghai and other provinces is minimum. Next with the help of GIS method the economic contribution coefficient and ecological carrying capacity coefficient of carbon emissions of each province were analyzed. Finally the fairness of carbon emissions for Chinese provinces was researched by the Gene coefficient.

8869-34, Session PMon

The study on the changing characteristics and their countermeasures for carbon emissions of China's in 2000-2010

Qiuxian Wang, Zhiqiang Gao, Jicai Ning, Yantai Institute of Coastal Zone Research (China)

Based on the quantitative calculation of 2000-2010 China's 30 provinces of carbon emissions by the method of 2006 IPCC with the data from China energy statistical yearbook and China cement Yearbook, a detailed analysis of the temporal and spatial variation characteristics of carbon emissions in both Chinese level and provinces' level was made. The result showed that most of the provinces of China's carbon emissions presented an increasing trend in the past 11 years, especially in Shandong Province, Hebei Province, Shanxi Province, Liaoning Province, Jiangsu province which is located in the national top five. Then on the basis of quantitative calculation, assuming that the external conditions of Chinese carbon emissions unchanged, the author guessed the carbon emissions for China in 2020. The result showed that a carbon emission of China in 2020 is so large that we must take urge measures to prevent the amount to be reached. According to the speculating result, the author put forward some countermeasures for China, such as speeding up the pace of industrial restructuring, searching for clean energy and other measures to reduce the carbon emissions of china.

8869-35, Session PMon

Preliminary study of a dust event over Beijing by using satellite data and ground-based measurements

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The present study focuses on an intense dust storm event from 26th April to 4th May in 2012 over Beijing. Multi-satellite observations and ground-based measurements are used to detect and analyze this event. The ground-based AERosol Robotic Network (AERONET) data at Beijing station show that the AOD550 value peaked at ~2.5 on 1st May during the event. Simultaneously, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) passed by Beijing on 1st May and an intense dust layer has been detected at the altitude of 4 to 4.5 km. The vertical distribution of total attenuated backscatter coefficient (TABC), volume depolarization ratio (VDR) and color ratio (CR) of CALIPSO data are analyzed on that specific day. Result shows a TABC above 0.0045 km-1sr-1in the feature layer as VDR and CR concentrates of 0.1 ~ 0.5 and 0.6-1.4 respectively. Additionally, results from a time series of (MODerate resolution Imaging Spectroradiometer) MODIS data also show an agreement that the AOD reach a peak on 1st May in that time period. Hence, consistency between satellite observations and ground-based measurements can be observed in some ways.

8869-36, Session PMon

Desertification assessment in the agro-pastoral transitional zone of north China (1982-2006) using GIMMS NDVI data

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The Agro-Pastoral Transitional Zone of North China belongs to the arid/

semi-arid area is the most sensitive area of global climate changes where the environment is very fragile. Pearson correlation analysis of annually integrated GIMMS NDVI (?NDVI) against annual rainfall for the period of 1982–2006 is conducted on a pixel-by-pixel basis. ?NDVI and Rain-use efficiency (RUE; the ratio of vegetation productivity to annual rainfall) dynamic trend during the period were analyzed, with using the Mann-Kendall nonparametric test and linear regression temporal trend analysis. The results showed that Pearson correlation analysis of annual ?NDVI and rainfall for the period in most parts of the study area was no significant correlated. Only a few areas showed a very significant correlation ($p<0.01$).The trend analysis of ?NDVI and RUE by Mann–Kendall test and linear regression temporal analysis methods show that vegetation changes mainly reflect an increasing trend, and a significant decrease trend in a small pixel proportion; The northeast and central parts of the study area are characterized by positive trends in RUE slope values whereas a few parts of the southwest negative. In general, the results of the two methods are consistent with the ?NDVI and RUE. Finally, further examination of the desertification tendency among different rainfall conditions was conducted in the study area. The range of 200-500mm rainfall can be seen a certain trend with increasing rainfall and desertification is less likely to occur and vegetation restoration capacity is also enhanced.

8869-37, Session PMon

Spatial and seasonal variation trends of MODIS aerosol optical depth in East China during 2000-2012

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Using MODIS/Terra derived Aerosol Optical Depth (AOD) at 0.55um we compare them with AERONET derived level 2.0 AOD including Hefei, Shouxian, Taihu and Hangzhou-ZFU in East China. Results of the validation indicate that MODIS data of all sites falling in expectations errors (±0.05 ±0.15) are larger than 66% reaching NASA design requirements, except for Taihu observation site accounted for 41% due to it is located in the lake area and surface reflectance estimated low leading to AOD values large. On the whole, they have a good consistency and MODIS data can meet the applicability analysis for the study area. MODIS/Terra derived AOD at 0.55um from 2000 to 2012 are used to analyze the spatio-temporal variation of AOD in East China, which indicates AODs are significantly affected by the topographic distribution with AODs are relativity low in high altitude mountainous and large in low-lying plains and basins. In addition to, human activities also have a certain impact on the distribution of AOD. AODs are generally higher in urban area than the surrounding area of the urban area and it is more obvious, especially in urban agglomerations such as the Yangtze River Delta. At the same time, AODs have obvious seasonal variations. AODs are generally high in spring and summer, while low in autumn and winter. According to the distribution of Angstrom exponent, we can conclude that aerosol particulate scale is large mainly affected by coarse particles in spring and winter, because it is easy to the occurrence of dust weather in spring and vegetation density decreases in winter. In summer and autumn, it is mainly affected by small-scale particles due to the abundant precipitation is able to wash away the large particles in air and fine particles generated mainly from human activities.

8869-38, Session PMon

The study on paddy evapotranspiration based on different models

Juan Du, Chaoshun Liu, East China Normal Univ. (China)

Based on the observed paddy micro-meteorology and crop growth data, the hourly and daily paddy evapotranspiration is estimated by using the Penman-Monteith model, the FAO Penman-Monteith equation, the Shuttleworth-Wallace model and the MICROWEATHER model, respectively. The simulation accuracy, mechanism and sensitivity of each model were compared. After being verified by measured micro-meteorology data, the MICROWEATHER model was taken as a standard, the hourly and daily evapotranspiration estimated by the S-W model was most close to that estimated by MICROWEATHER model. The linear regression coefficient between the S-W model and the MICROWEATHER model is highest and the root mean square error (RMSE) between the two models is lowest. The S-W model has the highest simulation accuracy, followed by FAO formula and the P-M model has the lowest accuracy. The sensitivity analysis of three models to leaf area index shows the P-M model is most sensitive to LAI, then the MICROWEATHER model and the S-W model is not sensitive to LAI. The sensitivity analysis of the FAO formula to the wind speed shows that the FAO formula is not sensitive to the wind speed and because it's calculation is easy and accuracy is high, the FAO formula can be used widely. The sensitivity analysis of the P-M model and the S-W model shows that the P-M model is most sensitive to the aerodynamic resistance ra, then the canopy resistance rc .The S-W model is most sensitive to raa , then rcs , relatively large sensitive to rsa and rss , and not sensitive to rca .

8869-39, Session PMon

NO2 long-term monitoring by satellite in the Pearl River Delta

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Recently, the air quality is deteriorating continuously, do serious harm to human health. In order to realize the spatio-temporal characteristics of NO2 and its anthropogenic influences in Pearl River Delta, we have analyzed the long-term NO2 column concentration variation before the 2010 Asian Games and its characteristics during the period of the 2010 Asian Games by using the NO2 product OMNO2e from the Ozone Monitoring Instrument (OMI). It shows that the annual average of the NO2 column concentration in the Pearl River Delta has a significant downward trend from 2005 to 2010: the total column concentration of NO2(TotNO2) in the atmosphere had decreased from 9.207?1015molec/cm2 to 8.173?1015molec/cm2, with an average annual growth rate of -2.247%; while the tropospheric column concentration of NO2(TropNO2) had decreased from6.685?1015molec/cm2 to 5.646?1015 1015molec/cm2, with an average annual growth rate of -3.109%. The ratio TropNO2/TotNO2 which can reflect the amount of NO2 exhausted by human activities also decrease form 0.726 in 2005 to 0.691 in 2010. Durning the 2010 Asian Games, the weekly average of the TropNO2 in Pearl River Delta was maintained at a lower level. The characteristics of NO2 average distribution in the Pearl River Delta is maximum in the geometric center, outwardly smaller, and the high value area of TropNO2 became less and less from 2005 to 2010. Foshan, Jiangmen and Kwangchowan are the most polluted areas durning the Asian Games. But because of linkage air quality guarantee measures in the Pearl River Delta during the 2010 Asian games, the air quality of Pearl River Delta is better than historical periods.

8869-40, Session PMon

Assimilation the observation for improved hydrologic and energy flux estimation using ensemble Kalman filter

Chaoshun Liu, East China Normal Univ. (China)

Hydrologic and heat fluxes from land surface are indispensable parts in the surface energy conversion and hydrological cycle processes. Estimation and prediction for fluxes have immense research significance in fields of environmental protection, agricultural production and climate prediction. Base on Community Land Model (CLM3.0), a hydrologic and energy flux assimilation system was developed for improved sensible and latent heat fluxs by using the Ensemble Kalman Filter (EnKF) algorithm to compromise the continuous solution of model simulation and the accuracy of observation. Data from three flux observatory sites of Ameriflux flux observational network (Chestnut Ridge, ARM SGP

Main and Tonzi Ranch) which standing for three different land surface conditions are engaged in parallel experiments to test the assimilation system. The results showed that regardless the underlying land surface condition, direct assimilation of sensible and latent heat fluxes can improve the estimates of total surface sensible and latent heat fluxes. Furthermore, comparing with mainstream study which focusing on assimilation of surface temperature and humidity to indirectly improve the fluxes prediction, the results of direct assimilation of surface water and heat fluxes is far better than the former. It is noteworthy that whether the estimates of observational error is precise or not will directly affect the assimilation results though errors from initial condition, observation and atmospheric forcing will make contributions simultaneously.

8869-41, Session PMon

Validation of aerosol optical depth and total ozone column in the ultraviolet retrieved from multifilter rotating shadowband

Chaoshun Liu, East China Normal Univ. (China) and Colorado State Univ. (United States); Maosi Chen, USDA UV-B Monitoring and Research Program, Natural Resource Ecology Laboratory, CSU (United States); Wei Gao, Key Laboratory of Geographical Information Science, Ministry of Education, ECNU (China) and Joint Laboratory for Environmental Remote Sensing and Data Assimilation (China) and USDA UV-B Monitoring and Research Program, Natural Resource Ecology Laboratory, CSU (United States)

Ultraviolet (UV) radiation has great impact on health effects, crop yield accumulation, and climate change. Atmospheric aerosols can help to regulate UV by scattering and absorbing. Analysis of ground-based UV measurements can add valuable understanding of the UV radiation present and its interaction with aerosols. Measurements of Ultraviolet Multifilter Rotating Shadowband Radiometer (UV-MFRSR) network, running by the U.S. Department of Agriculture (USDA) UV-B Monitoring and Research Program (UVMRP) at Colorado State University, were selected to retrieve the aerosol optical depth (AOD) in the UV spectral range, and compared with the Aerosol Robotic Network (AERONET) inversions derived from collocated CIMEL sun photometer. The intercomparison between UV-MFRSR AOD and AERONET AOD shows very good agreement with correlation coefficients on the order of 0.98-0.99, slope range from 0.95 to 1.0, and offsets less than 0.02. The results confirm the quality and accuracy of UV-MFRSR measurements.

8869-42, Session PMon

Spatial distribution of soil erosion in China coastal zone

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The coastal zone is very important in the world. China coastal zone was granted the first priority of developing economy in the late 1980s. Since then, high population density and rapid economic development hace caused intensive changes of LUCC in this zone. Those changes have lead to land degradation. Besides, China governments launched series of projects and policy to improve such problems. Those will inevitably cause to diverse spatial dynamics of land degradtion. However, the state of land degradation in certain time is still unknown. Soil erosion is an important indicator of land degradation.Therefore, we use RUSLE model anlyze the spatial pattern of soil erosion for 2000. By spatial analysis, we found that soil erosion in China coastal zone is not serious. Widespread soil erosion is only occurred on coastal zones in Shandong, Hainan and werstern Guangdong Province. Although rainfall eosivity factor(R) is higher in southern coastal zone, erosion tends to occur on the slopes with lower LS values in northern coastal zone than southern coastal zone. To improve soil eorosion in those areas, we should let governments put more funds to increase vegetation cover in north. Such study will provide helpful suggestions for governments to prevent soil erosion in coastal zone.

8869-43, Session PMon

Automatic selection of high-resolution remote sensing images segmentation scales and refinement using a multi-scale approach

Ruijuan Yin, East China Normal Univ. (China)

The advantages of object-based classification over the traditional pixel-based approach are well documented. However, which scale parameter is the appropriate scale is difficult to assess, and the choice of scale parameter is very important and has a great influence on the segmentation effectiveness. To date, the most common method to evaluate the quality of a segmentation method is subjective evaluation, which is a tedious process and lacking in stability and reliability. Thus, an objective and unsupervised method is proposed for selecting suitable parameters for a multi-scale segmentation to ensure best quality results. In this paper, a newly multi-scale method is introduced to improve the segmentation of a high spatial resolution (0.5m) satellite data. First, the weight values of different bands are defined based on the variance of bands themselves and the correlation between them. Secondly, 20 segmentations, with similarity and area thresholds ranging from 20 to 200 scale, step by 5, are created in Definiens Professional 8.7. The global intra-segment and inter-segment heterogeneity indexes are taken into account to identify the optimal segmentation scale. Then, a LSI method, which is evolved by landscape fragmentation index, is performed in every object to select under-segmentation objects and Local Moran's is identified as the whole scene to choose over-segmentation. Finally, the under- and over-segmentation regions are refined by (a) further segmenting under-segmented regions at finer scales, and (b) merging over-segmented regions with spectrally similar neighbors. This process leads to the creation of several three- or two-scale image segmentations. As a result, comparison of single- and multi-scale segmentation indicates that local statistics (Local Moran's and LSI method) can improve global segmentation quality.

8869-44, Session PMon

Analysis of non-point and point source pollution in China: case study in Shima Watershed in Guangdong Province

Huaiyang Fang, South China Institute of Environmental Sciences (China); Qingshui Lu, Yantai Institute of Coastal Zone Research (China) and South China Institute of Environmental Sciences (China); Zhiqiang Gao, Yantai Institute of Coastal Zone Research (China); Wei Gao, USDA UV-B Monitoring and Research Program and Center of Remote Sensing and Modeling for Agricultural (United States)

China economy has been rapidly increased since 1978. Rapid economic growth led to fast growth of fertilizer and pesticide consumption. A significant portion of fertilizers and pesticides entered the water and caused water quality degradation. At the same time, rapid economic growth also caused more and more point source pollution discharge into the water. Eutrophication has become a major threat to the water bodies. Worsening environment problems forced governments to take measures to control water pollution. We extracted land cover from Landsat TM images; calculated point source pollution with export coefficient method; then SWAT model was run to simulate non-point source pollution. We found that the annual TP loads from industry pollution into rivers are

115.0 t in the entire watershed. Average annual TP loads from each sub-basin ranged from 0 to 189.4 ton. Higher TP loads of each basin from livestock and human living mainly occurs in the areas where they are far from large towns or cities and the TP loads from industry are relatively low. Mean annual TP loads that delivered to the streams was 246.4 tons and the highest TP loads occurred in north part of this area, and the lowest TP loads is mainly distributed in middle part. Therefore, point source pollution has much high proportion in this area and governments should take measures to control point source pollution.

8869-1, Session 1

MODIS surface reflectance calibration with AVHRR for vegetation condition monitoring

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USDA National Agriculture Statistics Services (NASS) used a bi-weekly AVHRR (NOAA-19 satellite) normalized difference vegetation index (NDVI) composite to monitor crop vegetation condition. The AVHRR NDVI maps have been proven valuable in providing a spatially complete view of crop's vegetation condition. However, their relatively low spatial resolution of 1km cannot provide crop specific information. NASS currently is developing a new Web-based vegetation condition monitoring system - VegScape in which MODIS daily gridded Surface Reflectance L2G product MOD09GQ with Bands 1 and 2 at a 250-meter resolution are used to replace the AVHRR NDVI. It was found that NDVI images of AVHRR and MODIS illustrated significant difference if they were displayed in the same legend (color schema). This indicated that AVHRR and MODIS sensors had significant difference in red band and/or IR band surface reflectance responses. To keep the continuity of USDA NASS' vegetation condition monitoring, this paper proposed to calibrate the MODIS surface reflectance based on the AVHRR data product. In this paper, the daily MODIS surface reflectance product MOD09GQ data were first corrected to nadir view reflectance. The corrected time series data were then composed into weekly composite using maximum value composite method. The calibration was performed by correlating corresponding pixels of the same spectral bands of both AVHRR and MODIS data acquired at the same date. Two look-up tables of the spectral reflectance values cross the sensors were established. The preliminary results show that the visual difference between NDVIs from two sensors was effectively minimized.

8869-2, Session 1

Integrating remote sensing data from multiple optical sensors for ecological and crop condition monitoring

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Ecological and crop condition monitoring requires high temporal and spatial resolution remote sensing data. Due to technical limitations and budget constraints, remote sensing instruments trade spatial resolution for swath width. As a result, it is difficult to acquire remotely sensed data with both high spatial resolution and frequent coverage. A synthesized approach fusing multiple types of remote sensing imagery provides a feasible and economical solution for many application areas. In recent years, we have developed a Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) that allows fusing high spatial resolution data from Landsat (16-day, 30m) with high temporal resolution data from MODIS (daily, 500m). The fused reflectance products can provide synthesized images with MODIS revisit frequency and Landsat spatial details. In this presentation, we will demonstrate an operational data fusion framework based on STARFM for integrating existing MODIS data products and freely available Landsat data for ecological and crop condition monitoring. Improvements of data consistency between Landsat and MODIS will be discussed and demonstrated. Tests focus on a cloudy naturally vegetated area and a crop region. Our initial results show that the detailed spatial and temporal variability of the landscapes can be identified from the fused remote sensing data. Different spectral and temporal patterns for natural vegetation and crops can be found at the field scales in the study areas. The operational data fusion framework provides an alternative solution to build dense time-series images at high temporal and spatial resolution for ecological and crop condition monitoring.

8869-3, Session 1

Wheat growth monitoring with radar vegetation indices

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Microwave remote sensing can help in the monitoring of crop growth. Many experiments have been carried out to investigate the sensitivity of microwave sensors to crop growth parameters. These have clearly shown that canopy structure and water content can greatly affect the measurements. For agricultural crops this suggests that each general type needs evaluation, here we focus on wheat. Ground-based polarimetric scatterometers can be of value in these studies because they can provide continuous crop observations using multi-polarization, multi-frequencies, and various incidence angles. They have been extensively used in a frequency range from L-band to Ka-band. The Radar Vegetation Index (RVI) was proposed as a tool for monitoring crop growth because it was less sensitive to both incidence angle and environmental condition effects than basic polarimetric data. Only a few studies have attempted to relate the RVI to vegetation parameters. In this investigation, we examine the relationship between wheat biophysical variables and RVI based upon polarimetric radar data. Data were obtained using a ground-based multi-frequency polarimetric radar system that provided measurements every 10 minutes over a crop growing season. The results show that L-band RVI can be used to accurately retrieve growth parameters for wheat.

8869-4, Session 1

Measuring vegetation heights from high resolution stereo aerial photography

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In the United States, including Alaska, there are approximately 770 million acres of rangelands, natural landscapes valued for livestock production, biodiversity, and watershed services. Vegetation height and structure are critical indicators for assessing rangeland health with regard to wildlife habitat, estimating forage and browse, and estimating wildfire fuels. Conventional field monitoring methods provide high accuracy for these indicators; however, they are expensive and time consuming particularly for large areas. Moreover, despite the high quality elevation information that is achieved through ranging techniques (e.g., LiDAR), they lack the ability to provide optical information that is indispensable in delineating vegetation in rangeland. On the other hand, recent development in digital photogrammetry has stimulated a great interest in its application in large scale mapping, monitoring, and change detection applications.

This article presents the use of stereo-aerial imagery in mapping rangeland vegetation heights for use in broad-scale monitoring programs. Three overlapping color-infrared aerial images were taken with an UltraCamX sensor at a scale of 1:3200, with a base-to-height ratio of 1/5. Due to the absence of ground control information, three orientation approaches are evaluated and compared. The first approach

was an absolute orientation using the on board GPS and INS systems with fixed inner camera parameters as defined through the camera calibration report. In the second approach camera parameters where defined in a relative manner and the model was scaled using the base distance between the first two images in the model. The third approach determined both exterior and interior camera orientation parameters through a unified least squares process. The calculated sets of orientation parameters were comparable between the three approaches leading to insignificant differences among the generated elevation models. These results suggest that vegetation height indicators can be gathered remotely with limited field visits to collect ground control.

8869-5, Session 1

Comparison of Terra and Aqua MODIS measurements with drought event characterization over the northern United States

Xianjun Hao, John J. Qu, George Mason Univ. (United States); Xiaoxiong Xiong, NASA Goddard Space Flight Ctr. (United States); Di Wu, George Mason Univ. (United States)

Both Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) instruments have operated successfully over 10 years. Terra and Aqua MODIS calibration consistency over time and spatial regions is very important for accurate production of long-term consistent climate data records, which are invaluable for environmental monitoring and natural hazards detection. Since calibration accuracy, spectral, spatial, temporal and angular differences and other factors may contribute to the disparity between Terra and Aqua MODIS instruments, it is a challenging task to track Terra and Aqua MODIS calibration consistency. But, for climate extreme events, such as severe drought, both Terra and Aqua MODIS data products should demonstrate similar spatial and temporal patterns. In this study, consistency of Terra and Aqua high level data products was investigated, through characterization of drought events in year 2012 over the northern United States. Time series of spectral indices derived from both Terra and Aqua MODIS 8-day surface reflectances were used to characterize the impacts of drought on vegetation. The spatial distribution and temporal development of drought events in year 2012 were identified using time seris of Terra MODIS and Aqua MODIS, respectively. Then, the spatial and temporal patterns of severe drought events from Terra and Aqua MODIS measurements were compared. This approach provides an alternate approach to check the consistency of Terra and Aqua MODIS measurments.The results will be helpful to analyze the impacts of MODIS calibration consistency.

8869-6, Session 2

Integrated data fusion and bio-optical models for monitoring microcystin concentrations in Lake Erie

Ni-Bin Chang, Benjamine Vannash, Univ. of Central Florida (United States)

Blue-green algae or cyanobacteria are photosynthetic bacteria that require little energy for cell maintenance and growth, giving them a distinct advantage over competition. Population growth and agricultural activities have caused an influx of nutrients into Lake Erie, leading to eutrophic zones. These conditions result in the formation of algal blooms, some of which are toxic due to the presence of Microcystis (a cyanobacteria), which produces the hepatotoxin microcystin. Microcystis has a unique advantage over its competition as a result of the invasive zebra mussel population that filters algae out of the water column except for the toxic Microcystis. The toxin threatens human health and the ecosystem, and it is a concern for water treatment plants using the lake as a water source. In this paper, we have proposed an early warning system using integrated data fusion and bio-optical models to determine microcystin concentrations and distribution by measuring the surface reflectance of the water body using satellite sensors. The fine spatial resolution of Landsat is fused with the high temporal resolution of MODIS to create a synthetic image possessing both high temporal and spatial resolution. As a demonstration, the spatiotemporal distribution of microcystin within western Lake Erie is reconstructed using the band data from the fused products and applied machine-learning techniques. The capabilities of two bio-optical models, including two-band and three-band models, to identify the highly nonlinear relationship between microcystin concentration and surface reflectance were analyzed using four statistical indices. The two-band model shows larger potential to estimate microcystin concentrations in the lake.

8869-7, Session 2

Characterization of drought events over Nebraska using time series of MODIS measurements

Xianjun Hao, John J. Qu, Di Wu, George Mason Univ. (United States); Xiaoxiong Xiong, NASA Goddard Space Flight Ctr. (United States)

Agricultural production systems are susceptible to climate extremes, especially drought. It is critical to detect and characterize drought events so as to provide supports for decision makers to mitigate the impacts of potential disasters on agriculture. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard Terra satellite has successfully operated since December 1999. Time series of Terra MODIS measurements provides the potential towards spatial and temporal characterization of drought events through analysis of the water content and greenness of vegetation. In this study, time series of Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Normalized Difference Infrared Index(NDII) from Terra MODIS measurements were analyzed to investigate the drought events of year 2002 and year 2012 in the United States. Records of normal NDVI, NDWI and NDII values for each pixel, each 8-day period were constructed using MODIS data of time period without drought. Then, anomaly of NDVI, NDII, and NDWI for each of the 8-day period in drought year (2002 and 2012) were analyzed, using the Nebraska state as an example. The results demonstrated the spatial distribution and temporal development of severe drought events in year 2002 and 2012 clearly, thus can provide the capability to characterize drought events at moderate spatial and temporal resolution (500m and 8 days). Further integration of remote sensing measurements with weather observations at ground stations, and crop data will lead to in-depth understanding of drought impacts on crop yield.

8869-8, Session 2

Periodicity analysis for teleconnection signal propagation between sea surface temperature and forest greenness across North America

Ni-Bin Chang, Sanaz Imens, Univ. of Central Florida (United States)

The growth of forest is critically vulnerable to the change in rainfall and radiation than in air temperature. The amount of rainfall and cloudiness in the northeast region of the United States is assumed to be strongly affected by the Atlantic sea surface temperature (SST). The observational investigation of the relation between the greenness of three undisturbed forested areas in the Atlantic region and Atlantic SST is fundamental to understand the response of terrestrial ecosystems to climate change. Such teleconnection signals may also entail the change of natural variability associated with several hydrological parameters such as rainfall and runoff. We conducted short-term environmental change quantification using MODIS satellite images supplemented by Tropical

Rainfall Measuring Mission (TRMM) data. Wavelet analysis was employed to derive climate signals of SST and embedded precipitation patterns over the decadal timescale to illuminate the high frequency propagation effects on climate teleconnection. In this context, the effect of Atlantic and pacific SST on the spatial and temporal changes of the Enhanced Vegetation Index (EVI) in the two selected northeastern and northwestern pristine forest regions of the United States was examined by using MODIS satellite images from 2002 to 2010. Cross wavelet analysis was performed to search for new insight in regard to the influence of long-distance climate teleconnection on seasonality effect of vegetation cover based on EVI variations.

8869-9, Session 2

Microwave monitoring of the soil moisture

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Interrelations between the characteristics of the microwave emission field of moisted soil and of the soil liquid water content, soil density, temperature and mineralization level of liquid water are the properties studied both theoretically and by field measurements. Both research and field studies show that microwave radiometric measurements permit estimates of 7 to 10 moisture levels in the top 0.1 to 1.0 wavelengths of soil and 3 to 7 grades of the subsurface water level between 0 and 1.5-3.5 m.

The soil moisture is divided on the solidly-united, loosely-united, and free one. United moisture is the water adsorbing by ground particles surface and having the form of film with the thickness equaled no more of 6 to 8 molicular layers. The volume of united moisture in the soil layer is determined by the soil type and is fluctuated in the wide interval from 2-3 per cent for sandy soil to 30-40 per cent for clay and loess soils. United water is unattainable for the plants and do not influence on the salt regime of soil. That is why the monitoring system is to realize that kind of moisture classification in the soil.

The soil moisture is expressed in per cent of dry soil weight. The radiation models of the soil moistering for different types, taking into consideration of soil density, its temperature and salinity, were studied in the details. The data required for solution of the moisture problem can be obtained from the values of brightness temperature contrasts, degree of polarization and spectral characteristics at centimetre and decimetre wavwlengths. Wavelengths 2.25, 18 and 30 cm proved to be the most informative to solve this task. The microwave radiation model describing the land cover emittively under the conditions of heterogeneously moistened layer is based on the existence of vertical heterogeneity in the dielectric permeability coefficient: ??(1+0.5?s)2. The value of ? is informative indicator of the moisture soil variation. As soil moisture begin to grows the ? increases at first slowly, if soil was dry, then it increases more rapidly. Weak dependence of ? on the stage of initial moistening can be explained thereby the tied moisture is characterized by small dielectric permeability. The existence of knowledge base that kind and application of GIMS technology allow to solve the task of water content, Ws(z), diagnostics in the soil layer . Four major types of vertical moisture profiles have been identified from an analysis of the moistening characteristics of the various climatic zones in the Former Soviet Union. In other climatic zones it is necessary to have such identification. As a matter of fact the task is reduced to the function Ws(z) reconstruction when the values Wsi=Ws(zi) are known and the following conditions are satisfied:

?Ws / ?z |z=0 ? C, 0? Ws(z)?Ks(z),

where Ks(z) is the given function.

8869-10, Session 3

Estimation evapotranspiration over the large landscape by using remote sensing data

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Evapotranspiration is the important process of plant physiological and ecological, estimating and monitoring evapotranspiration are very useful for evaluation of the influence on the crop growth situation. Determination evapotranspiration over natural surface, the utilization of satellite remote sensing is indispensable. In this paper, a new method is established based on high resolution remote sensing data(TM/ETM) combination Penman-Monteith regional daily evapotranspiration calculation model. The key of the algorithm is used to calculate the Temperature–Vegetation Dryness Index (TVDI) based on an empirical parameterisation of the relationship between surface temperature (Ts) and vegetation index (NDVI), Ts and NDVI in combination can provide information on vegetation and moisture conditions at the surface. These results

indicate that the method is feasible?and VTCI is a close real—time drought monitoring approach?It is based on satellite derived information and combination with the meteorology data, and the potential for operational application of the method is therefore large.

8869-11, Session 3

Inter-sensor relationship of two-band spectral vegetation index based on soil isoline equation: derivation and numerical validation

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Differences in spectral response function among sensors have known to be a source of bias error in derived data products such as spectral vegetation indices (VIs). Numerous studies have been conducted to identify such bias errors by comparing VI data acquired simultaneously by two different sensors. Those attempts clearly indicted two facts: 1) When one tries to model a relationship of two VIs from different sensors by a polynomial function, the coefficients of polynomial depends heavily on region to be studied: 2) Although increase of the degree of polynomial improves the translation accuracies, this improvement is very limited. Those facts imply that a better functional form than a simple polynomial may exist to model the VI relationships, and also that the coefficients of such a relationship can be written as a function of variables other than vegetation biophysical parameters.

This study tries to address those issues by deriving an inter-sensor VI relationship analytically. The derivation has been performed based on a relationship of two reflectances at different wavelengths (bands), called 'soil isoline equation.' The derived VI relationship becomes a form of rational function with the coefficients that depend purely on the soil reflectance spectra. The derived relationship has been demonstrated numerically by a radiative transfer model of canopy, PROSAIL. It is concluded that a rational function is a good candidate to model inter-sensor VI relationship. This study also shows the mechanism of how the coefficients of such a relationship could vary with the soil reflectance underneath the canopy.

8869-14, Session 3

Simulation of regional rice growth by combination remote sensing data and crop model

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Science (China)

Remote sensing monitoring the macroscopic vegetation situation and reflecting environmental factors influence the results and the process of crops; Crop growth simulation model using environmental factors simulate the process of crop growth, revealing the cause and essence of the process, both of them have advantages and disadvantages. Thus developing the study of combine remote sensing yield estimation and dynamic crop growth model is essential, it is a significant scientific issue studying the approach and method which can combine these two advanced technologies. In this paper, using multi-temporal remote sensing information and crop model ORYZA2000 combined method realizing the rice growth simulation in pixel scale, after the comparison between simulated result and the actual statistic value, accuracy is high and result is good. The combination of remote sensing information and crop simulation model is a complex issue, its result will be affected by many factors, combined with the field test in this study is a simplification of the actual situation, this will certainly affect the result's accuracy.. This method has great practical significance and at the same time has positive application prospect. It can be used to monitor and evaluate crop growth condition, forecast crop yield and so on, thus can be used in decision support service on different regional scales and guiding agricultural production.

8869-45, Session 3

Spatial discretization of distributed hydrological response units for SWAT

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The world is experiencing increasingly more serious situation of water resources. The distributed hydrological model (DHM) has become the indispensable means for exploring the influences of climate change and human on hydrological cycles and water resources. With strict mathematical and physical description of hydrological processes, DHM could account the spatial variations of watershed parameters and horizontally relate different HRUs. Therefore, the Digital Terrain Model (DEM) based DHM is one major trend of hydrological modeling. Theoretically, the absolutely physical DHM is built on the strict hydrological processes. However, none of current DHMs can absolutely describe the strict hydrological processes, and most are based on some hypotheses. For the semi-distributed hydrological model, Soil and Water Assessment Tools (SWAT), Hydrological Response Units (HRU) is the basic modeling unit, defined by land use, soil and slope. Land surface patches within one Hydrological Response Units (HRU) should bear identical hydrological properties (including land use, soil, slope and management) and thus have similar hydrological responses. However, it is difficult to determinate the spatial locations and to describe the interactions between different HRUs. This study proposed one schema to discretize HRU for SWAT on the basis of generalized data input. Within a small watershed of Taihu Basin, the data of land use and soil were generalized for discretizing SWAT HRUs. The SWAT model was modified with the discretized HRUs. The resulted showed that the SWAT improved by discretization schema could be more sensitive the runoff lag process and thus achieved better simulation accuracy.

8869-46, Session 3

Using mixture tuned match filtering to estimate fractional vegetation area in an urban desert environment

Christa Brelsford, Arizona State Univ. (United States)

Estimating changes in fractional vegetation area in desert urban environments is necessary to accurately measure the effectiveness of water conservation programs that influence outdoor vegetation. Ground truth for fractional vegetation area was visually coded from one foot per pixel aerial photography for 1000 pixels across 9 LANDSAT images, and compared to the corresponding Mixture Tuned Match Filtering (MTMF) result. MTMF is a biased estimator of fractional vegetation area. Three methods of calibrating the MTMF results to match the mean and distribution of the ground truth results were tested: using logistic regression, OLS regression, and a mean shift transformation. After filtering the results over neighborhoods and calibrating raw MTMF results so that the MTMF mean is the same as the ground truth mean, calibrated MTMF is an acceptable measure of changes in fractional vegetation area in residential parcels in Las Vegas, NV.

8870-1, Session 1

Spectral imager based on Fabry-Perot interferometer for Aalto-1 nanosatellite
(Invited Paper)

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Aalto-1 is a 3U-cubesat project coordinated by Aalto University. The satellite will be mainly built by students as project assignments and thesis works and it will be launched in 2014. VTT Technical Research Centre of Finland is developing the main Earth observation payload, a miniaturized spectral imager, for the satellite. It is a novel miniaturized adjustable spectral imager. Mass of the spectral imager including electronics and mechanics of the spectral imager and visual camera will be 500 grams, and dimensions will be 80 mm x 80 mm x 45 mm. The spectral imager is based on a tunable Fabry-Pérot interferometer (FPI) accompanied by a RGB CMOS image sensor. The FPI consists of two metallic mirrors separated by a tunable air gap. The piezo-actuated FPI uses three piezo-actuators in a closed capacitive feedback loop for air gap tuning. The spectral resolution of the imager is 8 – 15 nm (FWHM) and the spectral range is 500 – 900 nm. Imaging resolution of the spectral imager is 1024x1024 pixels. The focal length of the preliminary optics is 32 mm and F-number is 3.4.

8870-2, Session 1

Alignment results for a high-performance thermal infrared imaging spectrometer for Earth science

William R. Johnson, Simon J. Hook, Steven Shoen, Bjorn T. Eng, Jet Propulsion Lab. (United States)

The Hyperspectral Thermal Emission Spectrometer (HyTES) was developed as part of the risk reduction activities associated with the Hyperspectral Infrared Imager (HyspIRI). Spectral band selection for HyspITIR requires high performance imaging spectroscopy which means minimizing any artifacts caused by the instrument such as smile and keystone distortion. The HyTES pushbroom design has 512 spatial pixels over a 50-degree field of view and 256 contiguous spectral bands between 7.5?m and 12?m in the thermal infrared (TIR) wavelength region. The instrument was flown on a twin otter aircraft during an engineering flight, and the results are promising. This paper describes pre-flight alignment results. The entire optical assemblies (both reflective and refractive components) as well as the focal plane array were held at cryogenic temperatures, so achieving precision optical alignment was extra challenging. A HyTES spectral response function (SRF), across track response function (ARF) and cross-track response function (CRF) were measured and are shown to be held at an acceptable level. The instrument turns out to have very low smile and keystone distortion which is a requirement for science data validity.

8870-4, Session 1

A fast, compact, configurable, thermal-infrared hyperspectral and chemical-specific contrast detection imager

Marsha Fox, Neil Goldstein, Pajo Vujkovic-Cvijin, Brian Gregor, Steven Adler-Golden, Jason Cline, Benjamin St. Peter, Spectral Sciences, Inc. (United States); Mark Wilder, Augustus Lowell, Triple Ring Technologies, Inc. (United States)

A second-generation, micro-electro-mechanical systems (MEMS)-based, hyperspectral imager will extend the previously developed Adaptive Multiplexing Spectrometer[1] breadboard into a compact, fully integrated unit. The system will produce hyperspectral imagery and chemical-specific thermal infrared contrast imagery for visualization, detection, and quantification of chemical species through their characteristic long-wave infrared spectral signatures. The slit spectrometer uses a set of concave gratings, a MEMS digital micro-mirror device (DMD), and a single-pixel Stirling-cooled detector to produce spectrally selective scene imagery. The image field-of-view is scanned by a movable, DMD-synchronized spectrometer slit to provide a second spatial dimension.

The sensor may operate in hyperspectral imaging mode; however its strength lies in producing hyperspectral detection filters in hardware to rapidly generate contrast imagery. This mode is accessed by implementing analog transmission functions with the DMD using grey scales. Thus linear algorithms, including traditional detection methods such as matched filters, orthogonal subspace projection, and principal component analysis, can be implemented in hardware. The firmware DMD programming will enable an operator to rapidly change operating mode and spectral, temporal and spatial resolution. For instance, the system can be programmed to operate on sub-arrays of pixels in order to more rapidly interrogate an area or collect high-resolution spectra.

The opto-mechanical, electronic, software and firmware designs of the new system will be described. Preliminary results, using a combination of first and second generation hardware and software will be presented for field image data collection, including hyperspectral and chemical-specific contrast detection imagery.

[1] Goldstein, N., M. Fox S. Adler-Golden and B. Gregor, “Infrared adaptive spectral imagers for direct detection of spectral signatures and hyperspectral imagery,” Proc. SPIE Vol 8618 (awaiting publication).

8870-5, Session 2

Observing system simulation experiments to evaluate the impact of remotely sensed data on hurricane track and intensity prediction
(Invited Paper)

Robert M. Atlas, National Oceanic and Atmospheric Administration (United States); George D. Emmitt, Simpson Weather Associates, Inc. (United States); Thomas S. Pagano, Jet Propulsion Lab. (United States)

Observing System Simulation Experiments (OSSEs) are an important tool for evaluating the potential impact of proposed new observing systems, as well as for evaluating trade-offs in observing system design, and in developing and assessing improved methodology for assimilating new observations. Extensive OSSEs have been conducted at NASA/ GSFC and NOAA/AOML in collaboration with Simpson Weather Associates and operational data assimilation centers over the last 27 years. These OSSEs determined correctly the quantitative potential for several proposed satellite observing systems to improve weather analysis and prediction prior to their launch, evaluated trade-offs in orbits, coverage and accuracy for space-based wind lidars, and were used in the development of the methodology that led to the first beneficial impacts of satellite surface winds on numerical weather prediction. OSSEs are currently being performed using combinations of global and regional models and data assimilation systems to evaluate the impact of hyperspectral sounders and advanced lidars on hurricane track and intensity prediction.

8870-6, Session 2

Lessons from the first 18 years of hyperspectral infrared sounder data *(Invited Paper)*

Hartmut H. Aumann, Jet Propulsion Lab. (United States)

As of the end of 2013 NASA and EuMetSat have accumulated 11 years of AIRS, 6 years of IASI and almost 2 years of CRIS data. In spite of major differences in key design areas, all three instruments continue to perform extremely well. A lot has been learned from the analysis the data and how some of the good capabilities and some of the performance liens of the three instruments in some cases are related to over- and under specifications of Functional Requirements, and how the use of even moderate size arrays can bring unexpected complications. Over-specification of requirements invariably leads to higher cost. All three instruments were nominally specified to support the National Weather Centers for short term weather forecasting with a five year lifetime. Not mentioned in the Functional Requirements, but now emphasized, are Climate research, Cross-calibration of vintage sounders and minor gas retrievals, although some of these potential capabilities were recognized before the launch of AIRS in 2002. We illustrate these points with specific examples from AIRS, IASI and CRIS. Future sounders from low Earth and geostationary obits are expected to be smaller, cheaper and more capable than the instruments they are intended to replace. We discuss highlights of what we have we learned from AIRS, IASI and CRIS, and how can this help in the Functional Specification and design of future infrared sounders.

As an example, the differences between spatially adjacent pixels in AIRS, IASI and CRIS are interpreted as geophysically significant if they exceed the random noise. Grossly un-physical differences are seen in images as “striping”. Experience with the calibration of arrays as small as 3x2x2 for IASI or 3x3x3 from CRIS, 2378x1 from AIRS shows that at the random noise level the radiometric calibration of each of the array elements over its full dynamic range is unique. The use of spatial differences at the random noise level was not stated explicitly in the functional requirements documents and is very difficult to achieve. Future sounders are expected to increasingly rely on large arrays and therefor have to account for the complications introduced by arrays with additional prelaunch calibration.

8870-7, Session 2

High performance Earth imaging and sounding from space using the hyperspectral MWIR

Thomas S. Pagano, Hartmut H. Aumann, Jet Propulsion Lab. (United States)

NASA’s Atmospheric Infrared Sounder (AIRS) is a hyperspectral infrared instrument that covers the infrared spectrum from 3.7-15.4 um with 2378 channels and flies on the EOS Aqua spacecraft. NASA’s MODIS instrument provides global daily imagery with 36 spectral bands ranging from 0.4-14.4 um at spatial resolutions ranging from 0.25 to 1.0 km at nadir. Both AIRS and MODIS have demonstrated considerable value to Earth science, natural and man-made hazards and disaster management and numerical weather prediction. These instruments have been succeeded by the Cross-track Infrared Sounder (CrIS) and the Visible and Infrared Imaging Radiometer Suite (VIIRS) on NPP and JPSS. While the performance of these systems is exceptional future requirements call for hyperspectral imaging and sounding in a combined observation at nominal spatial resolutions of 1-2 km.

Learning from the AIRS experience, excellent surface and atmospheric temperature and water vapor retrievals can be achived using a spectrometer covering the MWIR spectral range from 1950 cm-1 to 2450 cm-1 with 0.5 cm-1 sampling and 1.0 cm-1 spectral resolution. The MWIR is examined due to the lower cost of optical and detector materials and cooling requirements. The very high spectral resolution has not been examined before and will improve spectral and radiometric calibration accuracy and enable accurate surface temperature measurements using “superwindow” channels. Retrieval performance simulations for key parameters including the vertical resolution of temperature and water vapor profiles is examined and compared to state-of-the art AIRS retrievals. The ability to retrieve surface temperature and emissivity for land and ocean applications is also examined.

8870-8, Session 2

Error budget for a calibration demonstration system for the reflected solar instrument for the climate absolute radiance and refractivity observatory

Kurtis Thome, Joel McCorkel, Brendan McAndrew, NASA Goddard Space Flight Ctr. (United States)

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission addresses the need to observe high-accuracy, long-term climate change trends and to use decadal change observations as the most critical method to determine the accuracy of climate change. One of the major objectives of CLARREO is to advance the accuracy of SI traceable absolute calibration at infrared and reflected solar wavelengths. This advance is required to reach the on-orbit absolute accuracy required to allow climate change observations to survive data gaps while remaining sufficiently accurate to observe climate change to within the uncertainty of the limit of natural variability. While these capabilities exist at NIST in the laboratory, there is a need to demonstrate that it can move successfully from NIST to NASA and/or instrument vendor capabilities for future spaceborne instruments.

The current work describes the radiometric calibration error budget for the Solar, Lunar for Absolute Reflectance Imaging Spectroradiometer (SOLARIS) which is the calibration demonstration system (CDS) for the reflected solar portion of CLARREO. The goal of the CDS is to allow the testing and evaluation of calibration approaches, alternate design and/or implementation approaches and components for the CLARREO mission. SOLARIS also provides a test-bed for detector technologies, non-linearity determination and uncertainties, and application of future technology developments and suggested spacecraft instrument design modifications. The resulting SI-traceable error budget for reflectance retrieval using solar irradiance as a reference and methods for laboratory-based, absolute calibration suitable for climate-quality data collections is given. Key components in the error budget are geometry differences between the solar and earth views, knowledge of attenuator behavior when viewing the sun, and sensor behavior such as detector linearity and noise behavior. Methods for demonstrating this error budget are also presented.

8870-9, Session 3

Using a new GUI tool to leverage lidar data to aid in hyperspectral image material detection in the radiance domain on RIT SHARE LiDAR/ HSI Data

Emmett Ientilucci, Rochester Institute of Technology (United States)

This paper looks the hyperspectal and LiDAR component of a new multi-modal (freely available) data set (collected by the Rochester Institute of Technology) that has been designed to analyze the various impacts of illumination change on materials. Similar materials were placed on different backgrounds where spectral signatures were analyzed to determined impacts of background adjacency. Materials were also placed next to tree lines where they were fully illuminated but with the possible impact of tree shine. Hyperspectral, multispectral, and LiDAR modalities were used to image the materials in the above mentioned scenarios. Applications such as material detection with results are used

to assess difficulties with finding such materials. The detection is based on the generation of a forward sensor-reaching radiance model that incorporates parameters for shadowing, illumination angle variation, and in-direct sky loading. The incorporation of LiDAR into the physical models will aid in approximating the correct per-pixel signature to be used in the above mentioned material detection scheme. This technique can help mitigate issues related to varying illumination across a scene, for example. All of the processing (i.e., LiDAR data manipulation, MODTRAN (specific atmospheric model), HSI data and material detection) is performed in a new custom GUI tool which runs in the ENVI software. This makes processing and analysis very quick and efficient.

8870-10, Session 3

Calculation of LRCS of spatial object and its experimental verification

Yunhua Cao, Lu Bai, Haiying Li, Yanhui Li, Xidian Univ. (China)

Bi-directional Reflectance Distribution Function (BRDF) of some artificial satellite used materials such as solar panel, satellite coating material, OSR panel, and white paint at the wavelength of 1.06 micrometers is measured in laboratory. A five-parameter BRDF model is introduced, and BRDF models of these materials are established based on the measured BRDF data and the five-parameter model. With the obtained models, BRDF of these materials at arbitrary incident and reflected angle can be obtained.

A scaled geometrical model of a simple satellite with a cubic body and solar panel wing is established. Then the model is divided into small facets, and each facet is assigned with a known BRDF model. As Laser Radar Cross Section (LRCS) of each visible facet can be calculated with BRDF of the facet, LRCS of the satellite can be obtained by summating LRCS of each visible facet. LRCS of the satellite at different incident and reflected angles are calculated. The result shows that the main influence factors of LRCS of the satellite are the shape and BRDF of the material. The peak of LRCS of the satellite is very high at the specular reflection direction when the laser illuminates at facets with material of solar panel or OSR panel, and the value reduced quickly when the incident and reflected direction is away from the specular reflection direction. When the laser illuminated at facets with material of satellite coating material or white paint, LRCS varies slower.

Measurement system to measure LRCS of the satellite is established. The system mainly consists of laser emission unit, laser collimation and expending units, optical receiving units, signal processing unit, and signal display unit. LRCS of the scaled satellite model is measured with the measurement system. The measured data and calculated data are compared and show good consistency.

8870-11, Session 3

Imaging FTIR emissivity measurement method

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Though many materials behave approximately as greybodies across the long-wave infrared (LWIR) waveband, certain important infrared (IR) scene modeling materials such as brick and galvanized steel exhibit more complex optical properties. Accurately describing how non-greybody materials interact relies critically on the accurate incorporation of the emissive and reflective properties of the in-scene materials. Typically, measured values are obtained and used.

When measured using a non-imaging spectrometer, a given material's spectral emissivity requires more than one collection episode, as both the sample under test and a standard must be measured separately. In the interval between episodes changes in environment degrade emissivity measurement accuracy. While repeating and averaging measurements of the standard and sample helps mitigate such effects, a simultaneous measurement of both can ensure identical environmental conditions during the measurement process, thus reducing inaccuracies and delivering a temporally accurate determination of background or 'down-welling' radiation.

We report on a method for minimizing temporal inaccuracies in sample emissivity measurements. Using a LWIR hyperspectral imager, a Telops Hypercam, an approach permitting hundreds of simultaneous, calibrated spectral radiance measurements of the sample under test as well as a diffuse gold standard is described. In addition, we describe the data reduction technique to exploit these measurements.

Following development of the reported method, spectral reflectance data from 10 samples of various materials of interest were collected. These data are presented along with comments on how such data will enhance the fidelity of computer models of IR scenes.

8870-12, Session 3

Spectral reconstruction using spectrally tunable LED illumination

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Spectral imaging provides digital images with far more spectral information for each pixel than traditional color cameras. The raw data output is often visualized as a datacube. This can be thought of as a stack of tens to hundreds of pictures with each successive image representing its own specific color (spectral band), or equivalently, as a detailed spectral curve for each pixel.

Estimating the spectral reflectance of an object through low dimensional images require both image acquisition and a post spectral numerical estimation analysis. In this study, we implemented a system using a homemade cluster of LED light sources with different spectra to illuminate the scene and a conventional color CCD to acquire images. Also, integrating sphere supplies a stable and uniform lighting environment. We used principal component analysis and pseudo inverse transformation to reconstruct the image reflectance. Macbeth Color Checker was chosen to be the training target of our system, and the validity of spectral estimation of Macbeth Color Checker was preliminarily demonstrated.

The results of analyses were incorporated into the estimation transformation matrix. Optimal LED spectra used in the multichannel acquisition system were also designed. Through computer simulations, we confirmed that the estimation technique that incorporates PCA improves computation efficiency without expense of estimation accuracy.

8870-28, Session PMon

Spatial characteristics of Taiwan Banks with HJ-1A/1B imagery and multibeam sonar sounding data

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The sun glitter is caused by the direct reflection of the Sun light from the sea surface and it is an intensive interference factor in extraction of accurate oceanic information in conventional optical remote sensing of the oceans. However, as a strong signal, sun glitter has a high value in researches of ocean hydrodynamics or submarine bottom topographic remote sensing. For example, sand waves within the Taiwan Banks, a shoal lies the southern the Taiwan Strait, are frequently imaged by optical satellite sensors which contain sun glitter signals, because the water depths are shallow enough and the sand waves are high enough in this region.

Sun glitter is related to the sea surface roughness, and variations in the sea surface roughness due to submarine topography can result in modulation of the radiance intensity in optical imageries. So submarine topographic features are frequently observed in optical satellite images. The image features of sand wave ridges in the optical remote sensing images are of light and dark stripes.The sand wave and its ridge line can readily be identified and drawn from optical images with the help of image processing software, such as the ArcGIS platform.

In this paper, HJ-1A/1B imagery was used to observe the Taiwan Banks, a sea area between the East China Sea and the South China Sea. Cloud free HJ-1A/1B optical images with sun glitter signals received from 2009 to 2011 were selected and further processed. Based on the image features of sand waves , the spatial distributions of the Taiwan Banks were mapped. The wavelength and direction of sand waves were verified with multi-beam sonar sounding data, then the wavelength and direction of sand waves were measured and statistically analyzed. Results show that the Taiwan Banks lies in 117°14'-119°26'E, 22° 32.5'-23°49'N with an area of 16400 km2, and its length from east to west is up to 228 km, and its width in north-south direction is about 145 km. Statistics results also illustrate that the Taiwan Bank can be divide into three regions, the western region, middle region and eastern region according to their regional spatial characteristics of sand waves. The wavelength of sand waves in the western Taiwan Bank is in the range of 900~1200 m, 500~800 m in the middle, and 350~650 m in the eastern. In term of the direction, the western Taiwan Bank is northeast-southwest, while the middle and east regions of the Taiwan Bank are almost north-south.

8870-29, Session PMon

Effects of band selection on the hyperspectral classification

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In the hyperspectral theory, data reduction techniques play an important role in the classification processing as hyperspectral imagery contains an immense amount of data posing many challenging problems such as data storage, computational efficiency, and the curse of dimensionality. Hyperspectral band selection technique is a well-known dimensionality reduction approach which retains the physical meaning of the data. It selects a set of bands from the input hyperspectral dataset which comprises the information needed for subsequent hyperspectral image spectroscopy. The majority of the existing state-of-the-art dimensionality reduction methods set criteria to the spectral information which is derived by the whole wavelength in order to define the optimum spectral subspace. These criteria are not associated with the particular classification task but with the data statistics, such as correlation and entropy values. However, each spectral signature of a particular material has spectral characteristics which contribute to distinguish it from other spectral signatures at specific sequential wavelengths. This paper focuses on investigating the effects of band selection on the classification by exploiting the information of sequential bands. More precisely, it is explored 1) whether classification can be optimized when different set of initial bands is selected per category; 2) whether there is an optimum subset of sequential bands which lead to more accurate classification results. Experiments comprise application of a well-known classification method, the support vector machine (SVM), on real hyperspectral dataset using all the possible subsets of p sequential bands, where p is equal to the dimensionality of the signal subspace. Evaluation of the classification accuracy leads to remarkable conclusions.

8870-13, Session 4

Band selection for hyperspectral remote sensing data through correlation matrix to improve image clustering

Hamed Gholizadeh, Indiana Univ. (United States)

Hyperspectral remote sensing is capable of providing large numbers of spectral bands. The vast amount of data volume presents challenging problems for information processing, such as heavy computational burden. In this paper, the impact of dimension reduction (band selection) on hyperspectral data clustering is investigated from two viewpoints: 1) computational complexity; and 2) clustering performance. Clustering algorithms are built to solve the site labeling problem without the need for training samples. Therefore, clustering is one of the most useful tasks in data mining process for discovering groups and identifying interesting distributions and patterns in the data, and it has been subject of wide research since it arises in many application domains in engineering. So, investigating the impact of band selection on hyperspectral data clustering is justifiable. The proposed band selection method is based on thresholding the band correlation matrix and selecting the least correlated bands. Selected bands are then used to cluster the hyperspectral image. The number of clusters in this method is set equal to the signal subspace dimension inferred by the HFC method. Experimental results on a real-world hyperspectral remote sensing data proved that the proposed dimension reduction method will decrease computational complexity and lead to better clustering results compared to those of K-Means and Fuzzy c-Means in terms of the Calinski-Harabasz and Davies-Bouldin indices.

8870-14, Session 4

Behavioral model and simulator for a multi-slit optimized spectrometer (MOS)

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The Multi-Slit Optimized Spectrometer (MOS) is a NASA funded Instrument Incubator Program (IIP) to advance an innovative dispersive spectrometer concept in support of the GEO-CAPE ocean science mission. As part of the instrument's design and testing, we have constructed a 'behavioral model' of the instruments optical engine which allows an end-to-end simulation from input radiances to final product maps. The MOS SIMulator (MOS-SIM): (1) Allows the co-design of the instrument assembly and calibration test, (2) permits quantitative exploration of design trade-offs not just in terms of focal plane design metrics (e.g. optical distortions), but also the impact of design trade-offs on final product errors (e.g. remote sensing reflectances or chlorophyll concentration maps), and (3) enables the computation and tracking of `uncertainties' (means and standard deviations) at all stages of the image chain. We describe both the (behavioral) input-output map used for a rapid, but realistic, simulation of the MOS optical engine, as well as illustrative examples of quantitatively tracking errors in the imaging chain from input radiances to bounds on final product errors.

8870-15, Session 4

Simulation of imaging spectrometers degraded by satellite vibrations with pseudo cross-correlation theory

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During the spectral imaging course of imaging spectrometers, satellite platform's instability will bring serious impact on the imaging quality. The degradation mechanism of interferential and dispersive imaging spectrometers caused by satellite vibrations is studied in this paper. A simulation algorithm of degradation based on differential dynamic spectral imaging, and the theory of eight neighborhoods mixing pixels are put forward considering the affect of complex forms of vibration with high-order and multimode. Thus,we can get the point spread matrix, and build the relationship between the parameters of satellite vibration and the influences on spectral imaging using the pseudo cross-correlation theory. A spectral degradation method based on transforming the mixing matrix and a method based on pseudo cross-correlation theory are put

forward. Spectral degradation results are simulated by taking the spectral imaging data and the RGB color surface feature maps of remote sensing satellite as the ideal original data with the two methods separately. Simulation result shows that the degradation of the two methods are effective, reliable and coincident. The different application characters of the two methods are illuminated.

8870-16, Session 5

sCMOS detector for imaging VNIR spectrometry

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The facility Optical Information Systems (OS) at the Robotics and Mechatronics Center of the German Aerospace Center (DLR) has more than 30 years experience with high-resolution imaging technology. This paper shows the scientific results of the institute of leading edge instruments and focal plane designs for EnMAP VIS/NIR spectrograph. EnMAP (Environmental Mapping and Analysis Program) is one of the selected proposals for the national German Space Program. The EnMAP project includes the technological design of the hyperspectral spaceborne instrument and the algorithms development of the classification. The EnMAP project is a joint response of German Earth observation research institutions, value-added resellers and the German space industry like Kayser-Threde GmbH (KT) and others to the increasing demand on information about the status of our environment. The Geo Forschungs Zentrum (GFZ) Potsdam is the Principal Investigator of EnMAP.

DLR OS and KT were driving the technology of new detectors and the FPA design for this project, new manufacturing accuracy and on-chip processing capability in order to keep pace with the ambitious scientific and user requirements. In combination with the engineering research, the current generations of space borne sensor systems are focusing on VIS/NIR high spectral resolution to meet the requirements on earth and planetary observation systems. The combination of large swath and high spectral resolution with intelligent synchronization control, fast-readout ADC chains and new focal-plane concepts open the door to new remote-sensing and smart deep space instruments.

The paper gives an overview over the detector verification program at DLR on FPA level, new control possibilities for sCMOS detectors in global shutter mode and key parameters like PRNU, DSNU, MTF, SNR, Linearity, Spectral Response, Quantum Efficiency, Flatness and Radiation Tolerance will be discussed in detail.

8870-17, Session 5

Fabrication of low straylight holographic gratings for space applications

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The main challenges of fabricating diffraction gratings for use in earth monitoring spectrometers are given by the requirements for low straylight, high diffraction efficiency and a low polarization sensitivity. Low straylight gratings are the key component of imaging spectrometers with a high signal to noise ratio. Furthermore the use in space also requires a high environmental stability of these gratings.

We found that holography in combination with ion beam plasma etching provides a way to obtain monolithic, robust fused silica gratings which are able to meet the above mentioned requirements for space applications. Holography accompanied by plasma etching allows the fabrication of a wide range of different grating profiles to optimize the efficiency including the polarization behavior according to a wealth of applications. Typical profile shapes feasible are blazed gratings, sinusoidal profiles and binary profiles and this allows to tailor the efficiency and polarization requirements exactly to the spectral range of the special application. Holographic gratings can be fabricated on plane and also on curved substrates as core components of imaging spectrometers.

In this paper we present our grating fabrication flow for the example of plane blazed gratings and we relate the efficiency and straylight measurement results to certain steps of the process. The holographic setup was optimized to minimize straylight and ghosting recorded by the photoresist during the exposure. Low wavefront deviations require the use of highly accurate grating substrates and high precision optics in the holographic exposure.

8870-18, Session 5

Multislit optimized spectrometer for ocean color remote sensing: fabrication and assembly update

Tim Valle, Chuck Hardesty, Ball Aerospace & Technologies Corp. (United States); Curtiss O. Davis, Nicholas Tufillaro, Oregon State Univ. (United States); William S. Good, Chris Seckar, Peter Spuhler, Ball Aerospace & Technologies Corp. (United States)

The NASA ESTO funded Multislit Optimized Spectrometer (MOS) Instrument Incubator Program will advance a spatial multiplexing spectrometer for coastal ocean remote sensing from lab demonstration to flight-like environment testing. Vibration testing to meet the GEVS requirements for a geostationary orbit launch will be performed. The multiple slit design reduces the required telescope aperture leading to mass and volume reductions over conventional spectrometers when applied to the GEO-CAPE oceans mission. The MOS program is entering year 3 of the 3-year program where assembly and test activities will demonstrate the performance of the MOS concept. This paper discusses the instrument design, fabrication and assembly. It outlines the test plan to realize a technology readiness level of 6. Testing focuses on characterizing radiometric impacts of the multiple slit images multiplexed onto a common focal plane, and assesses the resulting uncertainties imparted to the ocean color data products. The MOS instrument implementation for GEO-CAPE provides system benefits that can lead to cost savings and risk reduction while meeting the science objectives of understanding the dynamic coastal ocean environment.

8870-19, Session 5

The CHROMA focal plane array: a large-format, low-noise detector optimized for imaging spectroscopy

Richard T. Demers, Robert B. Bailey, James Beletic, Steven G. Bernd, Sidharth Bhargava, Jason Herring, Jianmei Pan, Anders K. Petersen, Eric C. Piquette, Brian Starr, Matthew F. Yamamoto, Teledyne Imaging Sensors (United States)

The CHROMA (Configurable Hyperspectral Readout for Multiple Applications) is an advanced Focal Plane Array (FPA) designed for visible-infrared imaging spectroscopy. CHROMA has been integrated into a remote sensing, spectral imaging instrument. Using Teledyne's latest substrate-removed HgCdTe detector, the CHROMA FPA has very low dark current, low readout noise and stable quantum efficiency from the deep blue (390nm) to near the cutoff wavelength. CHROMA has a pixel pitch of 30 microns and is available in array formats ranging from 320?480 to 1600?480 pixels. Users generally disperse spectra over the 480 pixel-length columns and image spatially over the n?160 pixel-length rows, where n=2,4,8,10. The CHROMA Readout Integrated Circuit (ROIC) has Correlated Double Sampling (CDS) in pixel and generates its own internal bias signals and clocks. This paper presents the measured performance of the CHROMA FPA with 2.5 micron cutoff wavelength including the characterization of noise versus pixel gain, power dissipation and wavelength dependent quantum efficiency.

8870-20, Session 6

Hyperspectral imaging of rivers and estuaries *(Invited Paper)*

Curtiss O. Davis, Nicholas Tufillaro, Oregon State Univ. (United States)

The Hyperspectral Imager for the Coastal Ocean (HICO) is the first spaceborne imaging spectrometer designed to sample the coastal ocean. HICO samples selected coastal regions at 92 m ground sample distance with full spectral coverage (88 channels covering 400 to 900 nm) and a high signal-to-noise ratio to resolve the complexity of the coastal ocean. HICO has been operating on the International Space Station since October 2009 and collected over 7000 scenes for more than 50 users. We have been using HICO data to study major rivers and estuaries in the US and Asia. Our results show the advantages of HICO's additional spectral channels and higher spatial resolution for studying these complex coastal waters. We use this data to suggest requirements for spatial and spectral sampling for future ocean color sensors.

8870-21, Session 6

Overview of hyperspectral remote sensing for mapping marine benthic habitats from airborne and underwater sensors *(Invited Paper)*

Heidi M. Dierssen, Univ. of Connecticut Health Ctr. (United States)

The seafloor, with its diverse and dynamic benthic habitats varying on meter to centimeter scales, is difficult to accurately monitor with traditional techniques. The technology used to build imaging spectrometers has rapidly advanced in recent years with the advent of smaller sensors and better signal-to-noise capabilities that has facilitated their use in mapping fine-scale benthic features. Here, the use of such sensors for hyperspectral remote sensing of the seafloor from both airborne and underwater platforms is discussed. Benthic constituents provide a so-called optical fingerprint with spectral properties that are often too subtle to be discerned with simple color photographs or multi-channel spectrometers. Applications include the recent field validation of the airborne Portable Remote Imaging SpectroMeter (PRISM), a new imaging sensor package optimized for coastal ocean processes in Elkorn Slough California. In these turbid sediment-laden waters, only subtle spectral differences differentiate seafloor with sediment from that with eelgrass. Another example is the use of imaging spectrometers coupled with light sources on autonomous underwater vehicles for imaging deep water habitats of ecological significance. Here, results from the use of hyperspectral remote sensing to monitor white and orange cold corals in Norwegian waters are presented. The ultimate goal is to provide robust radiometric approaches that accurately consider light attenuation by the water column and are able to be applied to diverse habitats without considerable foreknowledge.

8870-22, Session 6

Investigating coral hyperspectral properties across coral species and coral state using hyperspectral imaging

Mehrube Mehrübeoglu, Texas A&M Univ. Corpus Christi (United States); Kevin B. Strychar, Grand Valley State Univ. (United States); Dustin K. Smith, Shane W. Smith, Texas A&M Univ. Corpus Christi (United States)

Coral reefs are one of the most diverse and threatened ecosystems in the world. Corals worldwide are at risk, and in many instances, dying due to factors that affect their environment resulting in deteriorating environmental conditions. Because corals respond quickly to the quality of the environment that surrounds them, corals have been identified as bioindicators of water quality and marine environmental health. The hyperspectral imaging system is proposed as a non-invasive tool to monitor different species of corals as well as coral state over time. This in turn can be used as a quick and non-invasive method to monitor environmental health that can later be extended to climate conditions. In this project, a laboratory-based hyperspectral imaging system is used to collect spectral and spatial information of corals. In the work presented here, MATLAB and ENVI software tools are used to view and process spatial information and spectral signature of to identify differences among the coral data. The results support the hypothesis that hyperspectral properties of corals vary among different coral species, and coral state over time, and hyperspectral imaging can be a used as a tool to document changes in coral species and state.

8870-23, Session 6

On the demands on imaging spectrometry for the monitoring of global vegetation fluorescence from space

Stefan Kraft, Umberto Del Bello, Matthias Drusch, Antonio Gabriele, Bernd Harnisch, European Space Research and Technology Ctr. (Netherlands); Jose Moreno, Univ. de València (Spain)

Vegetation fluorescence when measured from space contributes only a tiny fraction of the signal coming on top of the reflected radiance of the Earth. As a consequence, imaging spectrometers have to provide sufficient throughput and radiometric accuracy to enable accurate global monitoring of the daily to seasonal variations of the Earth's vegetation breath, which is particularly challenging if ground resolutions of a few hundred meters are targeted. Since fluorescence retrieval algorithms have to make corrections for atmospheric effects, it is necessary to provide sufficient spectral resolution, so that signal alterations due to the main parameters such as atmospheric pressure, temperature, aerosol density and height, and water vapour content can be accurately modelled. ESA's Earth Explorer 8 candidate mission FLEX carries a Fluorescence Imaging Spectrometer (FLORIS), which has been designed and optimised to enable such measurement. The spectrometer will measure in a spectral range between 500 and 780 nm and provide high spectral resolution of 0.3 nm in particular at the Oxygen A and B bands. It will also cover the photochemical reflection features between 500 and 600 nm, the Chlorophyll absorption band between 600 and 677 nm, and the red-edge in the region of 697 to 755 nm. FLEX will fly in formation with Sentinel 3 in order to further enhance the spectral coverage from measurements made by the Sentinel 3 instruments OLCI and SLSTR. We will report on the current status of the Phase A/B1 studies, and present the mission configuration and the identified instrument concepts.

8870-24, Session 6

Investigating oyster shell thickness and strength using three imaging modalities: hyperspectral imaging, thermal imaging and digital photography

Mehrube Mehrübeoglu, Delbert L. Smee, Petru-Aurelian Simionescu, Dustin K. Smith, Shane W. Smith, Texas A&M Univ. Corpus Christi (United States)

A comparative study of three imaging technologies has been conducted to non-invasively assess the thickness and strength of oyster shells

grown in various environmental conditions. Oyster shell thickness and strength are expected to be dependent on the harshness of the oyster's environment as well as other factors. Oysters have been grown in environments with and without predators, and within and out of tidal zones. Hyperspectral imaging has been used to detect possible differences in hyperspectral properties among oysters from each of the four environments. Thermal Imaging has been utilized to identify hot spots in the shells based on the principles of heat capacitance, indicating density or thickness of the shells. Finally, a visible-range digital photographic camera has been used to obtain digital images. The three technologies are compared to evaluate the effectiveness of each technology in identifying oyster shell thickness and strength. Although oyster shell thickness and strength are related, they may not be exactly correlated. The local thickness of the oyster shells have been measured with a micro caliper for stress measurement to establish a baseline and ground truth. The preliminary results from the three methods demonstrate that thermal imaging correlates the best with the invasive stress test results.

8870-25, Session 7

Extended hyperspectral imaging system modeling and implementation for subpixel target detection

Bo Ding, John Kerekes, Rochester Institute of Technology (United States)

In support of hyperspectral imaging system design and parameter trade-off research, an analytical end-to-end model to simulate the remote sensing system pipeline and forecast remote sensing system performance has been developed and made available to the remote sensing community through an RIT-hosted website. Users are able to forecast hyperspectral imaging system performance by defining an observational scenario along with imaging system parameters. For system modeling the implemented analytical model includes scene, sensor and target characteristics as well as atmospheric features, background spectral reflectance statistics, sensor specifications and target class reflectance statistics. For target detection applications, common data processing algorithms are also implemented. Predicted system performance has been verified by comparing the forecast results to ones obtained using real world data collected during the RIT SHARE 2012 collection. In this paper, a web-based application to model a remote sensing system is implemented and a typical application introduced. Sensor modeling has been extended to include the airborne ProspecTIR instrument. Subpixel target spectral radiance statistics are predicted by this model with given scene information, pre-measured background, target spectral reflectance statistics, and also the atmospheric radiative transfer model MODTRAN. The predicted spectral radiance statistics are transformed into a feature space and used with target detection algorithms to generate probability of detection versus false alarm curves to evaluate system performance and parameter trade-offs. The validation data from the SHARE 2012 collection show consistency with the simulated result. Also, some examples of parameter trade-offs are given and analyzed to explain the utility of this model for hyperspectral imaging system design and research.

8870-26, Session 7

Automated endmember determination and adaptive spectral mixture analysis using kernel methods

Robert S. Rand, National Geospatial-Intelligence Agency (United States); Amit Banerjee, Joshua B. Broadwater, Johns Hopkins Univ. Applied Physics Lab. (United States)

Various phenomena occur in geographic regions that cause pixels of a scene to contain spectrally mixed pixels. The mixtures may be linear or nonlinear. It could simply be that the pixel size of a sensor is too large so many pixels contain patches of different materials within them (linear), or there could be microscopic mixtures and multiple scattering occurring within pixels (non-linear). Often enough, scenes may contain cases of both linear and non-linear mixing on a pixel-by-pixel basis. Furthermore, appropriate endmembers in a scene are not always easy to determine. A reference spectral library of materials may or may not be available, yet, even if a library is available, using it directly for spectral unmixing may not always be fruitful. This study investigates a kernel-based fully-constrained method for spectral unmixing that attempts to determine if each pixel in a scene is linear or non-linear, and adapts to compute a mixture model at each pixel accordingly. The effort also investigates a kernel-based support vector method for determining spectral endmembers in a scene. Various scenes of hyperspectral imagery calibrated to reflectance are used to validate the methods.

8870-27, Session 7

Spatial heterodyne spectrometer: modeling and interferogram processing for calibrated spectral radiance measurements

Cara P. Perkins, John Kerekes, Michael Gartley, Rochester Institute of Technology (United States)

We present a model of spatial heterodyne spectrometer (SHS) and a corresponding interferogram-processing algorithm for the calculation of calibrated spectral radiance measurements. The SHS relies on Fourier Transform Spectroscopy (FTS) principles, and shares design similarities with the Michelson Interferometer. The advantages of the SHS design, including the lack of moving parts, high throughput, and instantaneous spectral measurements, make it suitable as a field-deployable instrument. Our SHS model takes into account the instrument's entrance optics, interferometer, exit optics, and detection scheme to output realistic, interferometric data. The model serves as a tool to find the optimal SHS diffraction grating and Littrow parameters for the desired design specifications and application. It also assists in the data analysis and system characterization. The interferogram-processing algorithm performs flat-fielding and phase corrections as well as apodization before recovering the measured spectral radiance via the Inverse Fourier Transform (IFT). The model and processing algorithm are tested with spectra generated by both MODTRAN and the Rochester Institute of Technology (RIT) micro-DIRSIG software as well as spectra recorded with a Designs & Prototypes Model 102 FTIR non-imaging spectrometer. The model and processing algorithm results shown are for a long-wave infrared (LWIR) SHS design. Operating in the thermal infrared, the SHS design presented provides the capability of performing chemical detection based on spectral signatures.

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8871-1, Session 1

Hyperspectral data compression using a Wiener filter predictor

Pierre V. Villeneuve, Scott G. Beaven, Alan D. Stocker, Space Computer Corp. (United States)

Application of compression methods to hyperspectral image (HSI) data is a significant technical challenge. A primary bottleneck in disseminating data products to the tactical user community is the limited communication bandwidth between the airborne sensor and the ground station receiver. This report summarizes a newly-developed algorithm (named “Z-Chrome”) for lossless compression of HSI data. This form of data is inherently highly correlated across spectral bands. Modern target detection algorithms typically exploit this correlation as a means to dramatically reduce false-alarm rates from scene clutter.

This algorithm is based on the assumption that compression of spatial information is separable from compression of spectral information. The Z-Chrome algorithm iterates over a sequence of band images from a data cube. At each step a Wiener filter predictor is constructed from the global spectral statistics between the current band and the already-processed data. The model prediction is subtracted from the current band, with the residual band image having spatial content that is now completely decorrelated spectrally from the residual data computed from all other bands. Existing image compression algorithms do a fantastic job at accounting for spatially-correlated image features. Z-Chrome is essentially a spectral-only predictor wrapped around state-of-the-art lossless image compression algorithms.

Z-Chrome algorithm performance is demonstrated by application to many hundreds of HSI data cubes collected by AVIRIS, Hyperion and CAP-ARCHER sensors over a variety of terrains. Quantitative lossless compression performance is measured at the cube level as the average number of bits per pixel. Relative compression performance is reported as the ratio of the compressed file size to the original file size.

8871-2, Session 1

An encoder rate control method for unidirectional distributed video coding

Juan Song, Peiyi Shen, Liang Zhang, Keyan Wang, Xidian Univ. (China)

Due to its good tradeoff between complexity and compression performance, distributed video coding (DVC) is widely used in video surveillance, wireless sensor network and etc. Most of DVC architectures available use a feedback channel to determine the required parity rate for decoding Wyner-Ziv frames. Therefore this kind of DVC architectures with feedback channel is called bidirectional DVC. However, a feedback channel is not always available for some applications or feedback cannot be used due to realtime demand, e.g. offline storage, realtime video streaming, and etc. To make DVC more practical, unidirectional DVC without feedback channel is presented, in which encoder rate control (ERC) is implemented to determine the required parity rate at the encoder. And to maintain low complexity at the encoder, the ERC module should be as simple as possible.

The ERC solutions in the literature either have quite poor performance or high encoder complexity. In this paper an efficient and low-complexity encoder rate control method is proposed. In our proposed method a low-complexity motion estimation method is first presented to create estimated side information at the encoder, in which the motion consistency between frames is utilized to reduce the search range and obtain accurate motion vectors. The motion search in the current frame is implemented based on the motion vectors in the previous frame. Then the created side information is used to estimate correlation noise and conditional entropy of each bitplane at the encoder. The inter-bitplane correlation of conditional entropy is utilized to simplify entropy computation. Finally the conditional entropy is adjusted as the estimated parity rate.

Experimental results show that our proposed encoder rate control method could estimate the required parity rate accurately with much lower complexity. And our ERC based unidirectional DVC system has comparable compression performance with bidirectional DVC.

8871-3, Session 1

Performance analysis of 2D asynchronous hard-limiting optical code-division multiple access system through atmospheric scattering channel

Yaqin Zhao, Xin Zhong, Di Wu, Ye Zhang, Guanghui Ren, Zhilu Wu, Harbin Institute of Technology (China)

Optical code-division multiple access (OCDMA) systems usually allocate orthogonal or quasi-orthogonal codes to the active users. When transmitting through atmospheric scattering channel, the coding pulses are broadened and the orthogonality of the codes is worsened. In truly asynchronous case, namely both the chips and the bits are asynchronous among each active user, the pulse broadening affects the system performance a lot.

In this paper, we evaluate the performance of a 2-D asynchronous hard-limiting wireless OCDMA system through atmospheric scattering channel. The distribution of multiple access interference (MAI) in truly asynchronous case is given. The BER decreases as the ratio of the chip period to the channel delay spread root mean square increases and the channel limits the bit rate to different levels when the chip period varies.

8871-4, Session 1

Lossless compression of multispectral images using adaptive edge-based prediction

Keyan Wang, Liping Wang, Juan Song, Yunsong Li, Rufei Cheng, Xidian Univ. (China)

Prediction-based coding approaches, owing to their high compression ratio and low complexity, are most popular methods for multispectral images lossless compression. However the existing methods did not fully exploit the edge information of the images. In this paper, we propose an algorithm for lossless compression of multispectral images with an adaptive edge-based prediction. The algorithm has two modes in prediction: intra-band and inter-band prediction. A similar median predictor (MP) is adopted In intra-band prediction, while in inter-band prediction a novel edge-based predictor (EP) is utilized. The EP applies an edge detection first to the reference band, and estimates the edge structure of the current band due to the strong inter-band structral similarity. After an edge-based analysis for the pixels within the context, the current pixel is predicted with the edge information from the context by least-squares optimization. All the predicted residuals are finally entropy coded. Experimental results show that the proposed edge-based prediction improves the lossless compression ratio by fully exploiting the high correlation of the pixels along the edges.

8871-5, Session 1

Improving multispectral satellite image compression using onboard subpixel registration

Mathieu Albinet, Roberto Camarero, Ctr. National d'Études Spatiales (France); Maxime Isnard, Thales Services (France); Christophe Poulet, Jokin Perret, EREMS (France)

Future CNES earth observation missions will have to deal with an ever increasing telemetry data rate due to improvement in resolution and addition of spectral bands. Current CNES image compressors implements a discrete wavelet transform followed by a bit plane encoding but only on a mono spectral basis and do not profit from the multispectral redundancy of the observed scenes. Recent CNES studies have proved a substantial gain on the achievable compression ratio, +20% to +40% on selected scenarios, by implementing a multispectral compression scheme based on a Karhunen Loeve transform followed by the classical DWT+BPE. But such results can be achieved only on perfectly registered bands and a deregistration as low as 0.5 pixel ruins all the benefits of multispectral compression.

In this work, we first study the possibility to implement a multi-bands subpixel onboard registration based on a registration grid generated on-the-fly by the satellite attitude control system and simplified registration and interpolation techniques. Indeed bands registration is usually performed on ground using sophisticated techniques too computationally expensive for onboard use. This fully quantized algorithm is tuned to meet acceptable registration performances within stringent image quality criteria and with the objective of onboard real-time processing. In a second part, we describe a FPGA implementation developed to evaluate the design complexity and, by extrapolation, the data rate achievable on a space-qualified ASIC. Finally, we present the impact of this approach on the processing chain onboard but also on ground and the impacts on the design of the instrument.

8871-6, Session 2

Fast implementation of neural network classification

Guiwon Seo, Jiheon Ok, Chulhee Lee, Yonsei Univ. (Korea, Republic of)

Most artificial neural networks use a nonlinear activation function that includes sigmoid and hyperbolic tangent functions. Most artificial networks employ nonlinear functions such as these sigmoid and hyperbolic tangent functions, which incur high complexity costs, particularly during hardware implementation. In this paper, we propose new polynomial approximation methods for nonlinear activation functions that can substantially reduce complexity without sacrificing performance. The proposed approximation methods were applied to pattern classification problems. Experimental results show that the processing time was reduced by up to 50% without any performance degradations in terms of computer simulation.

8871-7, Session 2

An efficient classification by signal subspace projection and partial filtering for hyperspectral images

Lena Chang, Zay-Shing Tang, National Taiwan Ocean Univ. (Taiwan)

Recently, some subspace-based techniques for hyperspectral image classification have received great attention, such as the orthogonal subspace projection (OSP), noise subspace projection (NSP) and signal subspace projection (SSP) methods. In this study, to reduce the computation complexity of hyperspectral data processing, we exploit high degree correlations in spectral and spatial domains, and propose an efficient classification method which combines SSP and partial filtering technique for hyperspectral images.

The SSP-based filters can be designed to extract target information using the signal subspace components corresponding to the image correlation matrix without a priori knowledge of background. Although SSP has been validated less sensitive to an inaccurate desired signature vector, it requires performing eigen-decomposition of image correlation matrix. To reduce computation complexity of SSP, we first examine the correlations between hyperspectral image bands and partition the original image bands into several groups by Maximum Correlation Band Clustering (MCBC) method. According to the spectrum correlations of ground truth data such as vegetation, cane or soil, each class is divided into corresponding band groups during training process. Instead of using all bands simultaneously, we design partial filter for each band group by SSP approach. Finally, the SSP-based partial filters (SSPPF) are combined using corresponding weights for each class. For real image classification, simulations validate the proposed SSPPF can achieve the performance of OSP and SSP with less computation complexity. Generally, the proposed method requires only 1/K^2 computations of SSP, if image is partitioned into K groups.

8871-8, Session 2

Fisher criterion based nearest feature line approach to land cover classification using multi source data fusion

Yang-Lang Chang, Yi-Shiang Fu, Tung-Ju Hsieh, National Taipei Univ. of Technology (Taiwan); Lena Chang, National Taiwan Ocean Univ. (Taiwan); Chin-Chuan Han, National United Univ. (Taiwan); Bormin Huang, Univ. of Wisconsin-Madison (United States)

In this paper a novel technique, known as nearest feature line (NFL) approach, is proposed for supervised classification of multisource images for the purpose of landslide hazard assessment. This approach presents a framework for data fusion of multisource remotely sensed images, which consists of two approaches, referred to as band generation process (BGP) and Fisher criterion based NFL classifier. It is developed for land cover classification based on the fusion of remotely sensed images of the same scene collected from multiple sources. Compared to the original NFL, we propose an improve NFL classifier which uses the Fisher criterion of between-class and within-class discrimination to enhance the original one. In the training phase the labeled samples are discriminated by the Fisher criterion, which can be treated as a pre-processing of NFL. The classification results can be obtained by NFL algorithm. In order for the proposed NFL to be effective for multispectral images, a multiple adaptation BGP is introduced to create a new set of additional bands especially accommodated to landslide classes. Experimental results demonstrate the proposed BGP/NFL approach is suitable for land cover classification in earth remote sensing and improves the precision of image classification.

8871-9, Session 2

Saline-alkali land classification using MODIS data In Western Jilin Province, China

Lingjia Gu, Ruizhi Ren, Jilin Univ. (China); Junsheng Cao, Changchun Institute of Optics, Fine Mechanics and Physics (China); Jian Sun, Jilin Univ. (China)

As an environmental disaster, soil salinization leads to a significant land degradation, furthermore, reduces or destroys soil productivity, which decreases food production in agricultural areas and makes serious threats to the sustainable development of ecology and national economy. Remote sensing technology can obtain useful information of observation

areas, and provide reliable data for ground monitoring, which is widely used in dynamic monitoring and resources research of saline-alkali land. The level of salt accumulation in saline soil directly causes different changes in spectral remote sensing image, which can be used to distinguish the image characteristics of normal soils from saline-alkali lands. Furthermore, the salinization degree can be induced from the spectral characteristics of saline-alkali land. Considering that the spectral reflection of saline-alkali land changes seasonally, it needs integrated experiences and pre-knowledge in order to reduce the classification error and statistical error. In this study, western Jilin Province, China selected as the observation area has a lot of typical characteristics of saline-alkali land. Firstly, the geographical location of the saline-alkali land was roughly determined according to the colors and shapes of MODIS image. Through obtaining and analyzing of the spectral characteristics of saline-alkali soil types, the relationship between the spectral characteristics of saline-alkali soil types and saline-alkali land classification was further established based on the existing empirical knowledge. The research results demonstrated that the saline-alkali lands located in Western Jilin Province, China can be effectively classified based on the spectral characteristics of MODIS data.

8871-10, Session 3

Multi-watermarking scheme for copyright protection and content authentication of DubaiSat-1 satellite imagery

Saeed H. Al-Mansoori, Emirates Institution for Advanced Science and Technology (United Arab Emirates); Alavi Kunhu, Khalifa Univ. of Science, Technology and Research (United Arab Emirates)

This paper exams applying watermarking scheme based on invisible frequency domain approach, called “Discrete Cosine Transform” (DCT), on satellite imagery. This technique emerged as a result of new challenges with piracy of remote sensing imagery ownership. This led researchers to look for different means to secure the ownership of satellite images and preventing the illegal use of these resources. Therefore, Emirates Institution for Advanced Science and Technology (EIAST) proposed utilizing existing data security concept by embedding a digital signature, “watermark”, into DubaiSat-1 satellite images. In this study a gray scale EIAST logo is embedded into DubaiSat-1 satellite imagery, which would protect the organization’s intellectual property against different image processing manipulation (i.e. attacks) attempts. Two criteria’s were set to evaluate the proposed algorithm: the quality of the watermarked image and the robustness of the technique against attacks. Image processing manipulations were used to generate numerous attacks such as lossy compression (JPEG), rotation, flipping , and noise addition (Salt & Pepper and Gaussian).

8871-11, Session 3

Anomaly-specified virtual dimensionality

Chein-I Chang, Shih-Yu Chen, Drew Paylor, Univ. of Maryland, Baltimore County (United States)

Virtual dimensionality (VD) has received considerable interest with its use in specifying the number of spectral distinct signatures, denoted by p. Unfortunately, no specific definition is provided by VD for what a spectrally distinct signature is. This paper presents a new concept, referred to as anomaly-specified VD (AS-VD) which determines the number of anomalies of interest present in the data. Specifically, two types of anomaly detection algorithms are of particular interest, sample covariance matrix K-based anomaly detector developed by Reed and Yu, referred to as K-RXD and sample correlation matrix R-based RXD, referred to as R-RXD. Since K-RXD is only determined by 2nd order statistics compared to R-RXD which is specified by statistics of the first two orders including sample mean as the first order statistics, the values determined by K-RXD and R-RXD will be different. Experiments are conducted in comparison with widely used eigen-based approaches.

8871-13, Session 3

Spatial corrlations constrained sparse unmixing of hyperspectral image using Markov random fields

Jiaojiao Li, Xianyun Wu, Yunsong Li, Keyan Wang, Xidian Univ. (China)

Spectral unmixing is an important research hotspot for remote sensing hyperspectral image. The unmixing process is comprised of the extraction of spectrally pure signatures(also called endmembers) and the determination of the abundance fractions of endmebers. Due to the inconspicuous signatures of pure spectra and the challenge of inadequate spatial resolution, sparse regression(SR) techniques are adopted in solving the linear spectral unmixing problem. However, these SR-based solutions failed to make full use of the spatial information. In this paper, we describe the classic sparse regression formulation firstly and then propose a new unmixing algorithm which involving in more complete spatial information on sparse unmixing formulation for hyperspectral image. The new algorithm integrates the spectral and spatial information in a Bayesian framework which is introduced to exploit the spatial-contextual information effectively. Moreover, the Markov Random Fields(MRF) can model the spatial correlation efficiently, the new method employ a MRF based on the Bayesian framework. Compared with other SR-based linear unmixing methods, our experimental results showed that the method proposed in this paper not only improves the characterization of mixed pixels but also obtains better accauracy in hyperspectral image unmixing.

8871-14, Session 3

Early warning of malaria at Bikaner, Rajasthan in India using AVHRR-based satellite data

Leonid Roytman, Nizamuddin Mohammad, The City College of New York (United States); Kawsar A. Akhand, The City Univ. of New York (United States); Felix Kogan, National Environmental Satellite, Data, and Information Service (United States); Mitchell Goldberg, National Oceanic and Atmospheric Administration (United States)

A better understanding of the relationship between satellites observed vegetation health, and malaria epidemics could help mitigate the worldwide increase in incidence of mosquito-transmitted diseases. This research investigates last 17-years association between vegetation health (condition) index and malaria transmission in Bikaner, Rajasthan in India an arid and hot summer area. The vegetation health (condition) index, derived from a combination of Advanced Very High Resolution Radiometer (AVHRR) based Normalized Difference Vegetation Index (NDVI) and 10-?m to 11-?m thermal radiances, was designed for monitoring moisture and thermal impacts on vegetation health. We demonstrate that thermal condition is more sensitive to malaria transmission with different seasonal malaria activities. The weekly VH indices were correlated with the epidemiological data. A good correlation was found between malaria cases and Temperature Condition Index (TCI) one at least two months earlier than the malaria transmission season. Following the results of correlation analysis, Principal Component Regression (PCR) method was used to construct a model of less than 10% error to predict malaria as a function of the TCI.

8871-15, Session 4

GPU-based parallel design of vertex component analysis for hyperspectral unmixing

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The vertex component analysis (VCA) algorithm is one of the most popular methods for spectral unmixing of hyperspectral data. This unsupervised algorithm is based on the geometry of convex sets. Compared with several existing state-of-the-art methods for endmember unmixing, such as pixel purity index (PPI) and N-FINDR, VCA genrally shows superior performance. Experiments with real hyperspectral data show that this algorithm is an effective tool to unmix linear mixtures of endmember spectra from hyperspectral data. In recent years, graphics processing units (GPUs) have become a widely used technology for general-purpose parallel computing. Massively parallel computations using GPUs have been applied in different areas. Considering the matrix/vector operations and computationally expensive calculations involved in the VCA algorithm, we can conclude that this method is suitable to be implemented on GPUs. In this work, we propose a parallel version of VCA on GPUs which is based on the Compute Unified Device Architecture (CUDA). We choose CUDA as our research platform as it is a well-established scheme in many applications. Different experiments are conducted with our parallel version in order to find its optimal implementation. After applying the algorithm to real hyperspectral data, our GPU implementation shows a speedup of 24.65x with regards to an optimized serial version of the algorithm.

8871-16, Session 4

Parallel acceleration for neural networks algorithms in hyperspectral image unmixing

Xianyun Wu, Jiaojiao Li, Yunsong Li, Keyan Wang, Xidian Univ. (China)

In hyperspectral imagery, mixed pixels are a mixture of distinct substances with linear or nonlinear interactions. Spectral unmixing aims at decomposing the mixed spectral signature into a collection spectrally pure constituent spectra which called endmembers and estimating the abundances of each endmember present in the mixture. Several algorithms have been proposed for spectral unmixing. Neural networks algorithms have shown good capabilities in solving nonlinear inversion problems in hyperspectral image unmixing. In NN-based unmixing algorithms, the Multi-Layer Perceptron(MLP) neural network scheme is trained for the pixel-based classfication algorithm. For the output response, "winner-takes-all" rule is replaced by a soft interpretation to give the percentage with each land cover classes. Compared with Linear Spectral Unmixing(LSU), the NN-based algorithm can obtain better performance. However, NN-based algorithm are usually highly time-consuming and hard for on-board or real-time processing. In this study, we use Graphic Processing Units(GPU) for faster parallel computing. We use Compute Unified Device Architecture(CUDA) language for efficient implementation of NN. For MLP scheme, each layer is independent with others and the learning process for each layer is identical with others. In the same layer, each note is also independent with other notes which make NN very suitable for parallel computing. Our implementation are deep optimized by using shared memory. Experimental results showed that our implementation achieve a very high speedup and identical results compared with single-thread CPU implementation.

8871-17, Session 4

An FPGA implemented bridge over water recognition for an image evaluation on-board of satellites

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In the present study, a novel approach for an automatic bridge over water recognition is introduced.

The method requires no a-priory knowledge about the scene, is applicable to optical gray value satellite image data and is implemented in a small reconfigurable micro chip, a Field Programmable Gate Array (FPGA).

Due to the low power consumption of the FPGA and the autonomous performance of the algorithm the implementation is suitable for an application on-board of satellites.

Since the captured satellite image data can be evaluated within a few seconds, useful information about the infrastructure, which is e.g. desired by the disaster management in case of a natural hazard, can be provided in a short time.

The proposed method is robust and recognizes the whole bridge deck area, which yields additional information about the bridge and allows a detailed analysis of the site. At first a binary water mask is derived from the satellite image data and all islands, hollow spaces in the water areas, are labeled.

Then all potential bridge regions are extracted by morphological operations. Because this step produces also a lot of false detections, a final analysis is carried out to separate real bridges from false ones. The result is a map of marked bridge deck areas.

The hardware implementation, in a Xilinx Spartan 3E FPGA, was tested with 40 panchromatic and near-infrared images with a spatial resolution of 5m, and showed promising results.

Hence, this method seems a reasonable tool for an image evaluation on-board of satellites.

8871-18, Session 4

Massively parallel computation of soil surface roughness parameters on a GPU

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Surface roughness is description of the surface micro topography of randomness or irregular. The standard deviation of surface height and the surface correlation length describe the statistical variation for the random component of a surface height relative to a reference surface. In the observation of the earth using microwave radiometers, surface roughness is an important factor to soil microwave radiation. When the number of data points is large, calculation of surface roughness parameters is time-consuming. With the advent of Graphics Processing Unit (GPU) architectures, inherently parallel problem can be effectively solved using GPUs. In this paper we propose a GPU-based massively parallel computing method for 2D soil surface roughness estimation. In this paper we develop a GPU-based high performance computing on the study of soil surface roughness parameters with total data points of 47,958. We reach a speedup of 115? as compared to a single threaded CPU version when I/O transfer is taken into account. The result can be used to IEM (Integrated Equation Model), and the soil backward scattering coefficient will be obtained.

8871-19, Session 4

A novel VLSI architecture for pixel purity index algorithm

Fang Yi, Jie Guo, Yunsong LI, Xidian Univ. (China)

In hyperspectral remote sensing, a single pixel of usually covers several different materials, and its observed spectrum can be expressed as a linear combination of a few pure spectral signatures called “endmembers”. One of the most popular endmember extraction algorithms is the Pixel Purity Index (PPI) which is time-consuming and hard to meet the on-board demands.

In this paper, we present a novel architecture for PPI algorithm on Field Programmable Gate Arrays (FPGA) to meet the on-board demands. The parallel architecture and pipelining technique enhance the processing capacity significantly. We also overcome a burden of huge I/O communication by optimizing the matrix multiplying strategy. Additionally, high-level synthesis tool is used. Based on above methods, our implementation is significantly time saving than other architectures in the same hardware device.

Our system architecture can be easily transplanted to different FPGAs by doing some configurations. In this paper, we implemented it on a System-on-Chip platform and a Virtex-4 XC4VFX60 FPGA. However, we recommend System-on-Chip platform due to its low-weight and low-power features for an entire remote data processing system.

We evaluated our algorithm using the well-known “Cuprite” image and take a comparison with ENvironment for Visualizing Images (ENVI) software. The U.S. Geological Survey library (USGS) is used to assess the accuracy of endmembers we extracted. It demonstrates that our hardware implementation can get equivalent or better accuracy in few seconds while the software runs more than one thousand seconds in a typical computer. This processing speed can meet the on-board demands.

8871-20, Session 4

Parallel processing of point cloud registration

Wen-Han Hsu, Tung-Ju Hsieh, Yang-Lang Chang, National Taipei Univ. of Technology (Taiwan); Bormin Huang, Univ. of Wisconsin-Madison (United States)

Recently, researchers use linear mode to set up a scanner to scan the landscape. It has been proven that the rotation along the z-axis has minimum effect on the accuracy of point cloud registration. In this study, we perform point cloud registration of two set of point cloud measured from different locations. The first set of point cloud remained unmoved. We perform point registration by introducing offsets along the x, y, and z direction to the second set of point cloud. The following steps are performed: First, we use RiSCAN PRO software to manually perform coarse registration by selecting matching points in two sets of point cloud. Second, we perform feature extraction and undergo sequential enumeration method to match point cloud pairs by introducing offsets to the second set of point cloud. Third, we perform sequential combination to fully enumerate offsets to find the optimal. We use Compute Unified Device Architecture (CUDA) to program GPU to achieve parallel computing and achieve a speedup factor of 90x.

8871-21, Session 5

Data fusion of hyperspectral and multispectral remote sensing data for near real-time monitoring of microcystin distribution in Lake Erie

Ni-Bin Chang, Univ. of Central Florida (United States)

Urban growth and agricultural production have caused an influx of nutrients into Lake Erie, leading to eutrophic zones. These conditions result in the formation of algal blooms, some of which are toxic due to the presence of Microcystis (a cyanobacteria), which produces the hepatotoxin microcystin. Microcystis has a unique advantage over its competition as a result of the invasive zebra mussel population that filters algae out of the water column except for the toxic Microcystis. The toxin threatens human health and the ecosystem, and it is a concern for water treatment plants using the lake water as a tap water source. This paper demonstrates the prototype of a near real-time early warning system using Integrated Data Fusion techniques with the aid of both hyperspectral (MERIS) and multispectral (MODIS) remote sensing data to determine spatiotemporal microcystin concentrations. The finer spatial and temporal resolution of MODIS is fused with the high spectral resolution of MERIS to create a synthetic images on a daily basis. As a demonstration, the spatiotemporal distributions of microcystin within western Lake Erie is reconstructed using the band data from the fused products and applied machine-learning techniques. Analysis of the results through statistical indices confirmed that the this type of algorithm has better potential to accurately estimating microcystin concentrations in the lake, which is better than all current 2-band and 3-band models and other computational intelligence models.

8871-22, Session 5

Enhancing DubaiSat-1 satellite imagery using a single image super-resolution

Saeed H. Al-Mansoori, Emirates Institution for Advanced Science and Technology (United Arab Emirates); Alavi Kunhu, Khalifa Univ. of Science, Technology and Research (United Arab Emirates)

DubaiSat-1 (DS1) captures multispectral images, which consist of three visible channels and one NIR with 5-meter resolution and a panchromatic channel with 2.5-meter resolution. Considering these resolutions, some important details might appear blurry on the image. Therefore, the concept of “Super Resolution” has been introduced to reconstruct the image in a way to overcome the inherent resolution limitations of imaging sensors. The aim of this study is to enhance the quality of the image by artificially increasing the number of pixels within the image to sharpen out-of-focus details or smooth rough edges in DubaiSat-1 images that have been enlarged using a general up-scaling process. Usually, images received from satellites go through many image processing and enhancement steps to increase the quality of these images. Many studies have been conducted in this field, and different techniques were suggested to improve the enhancement procedure. Studies were done to combine low resolution images of the same area to come up with an image with a high resolution and better quality. Image enhancement refers to operations used to get image features such edges, boundaries, or contrast in order to make a digital image more useful for display and analysis. In this paper , three common super-resolution techniques (i.e. Bi-linear Interpolation, Bi-Cubic Interpolation, Sparse Representation) are implemented on a single low resolution image and analysed when applying a specific sharpening filter.

8871-23, Session 5

High-resolution satellite image recovery by MTF compensation method using phase congruency estimation

Xiaopeng Shao, Zhenhua Jin, Juan Du, Xidian Univ. (China); Hong Chang, Weihai Vocational College (China)

Satellite imagery always has low-resolution causing poor application in practice because the serious degradation in imaging is resulted in many factors such as atmospheric turbulence, cloud, and aberration of optical system. To reconstruct the degraded remote sensing images with a high quality, we designed an algorithm to estimate the system modular transfer function(MTF) accurately. Phase congruency is employed to detect the edges and corners of the image first, then the significant edges, which are utilized to estimate the edge spread function(ESF) using inclined edge method, are picked up from above features through a certain line detection measurement. An image restoration algorithm based on total variation(TV) is introduced to deconvolute the degraded image with the estimated MTF which is derived from the ESF. The experiments show that this method is adaptive and efficient to recover the remote sensing images taken from a Chinese Satellite. The restored images with a higher resolution and higher signal-to-noise ratio(SNR) will improve the applications greatly.

8871-24, Session 5

Progressive band processing of anomaly detection

Chein-I Chang, Shih-Yu Chen, Robert C. Schultz, Yulei Wang, Univ. of Maryland, Baltimore County (United States); Chunhong Liu, South China Agriculture Univ. (China)

Band selection (BS) has advantages over data dimensionality in satellite communication and data transmission in the sense that the spectral bands can be tuned by users at their discretion for data analysis, while preserving data fidelity. However, to materialize BS in such practical applications several issues need to be addressed. One is how many bands required for BS. Another is how to select appropriate bands. A third one is how to take advantage of previously selected bands without re-implementing BS. Finally and most important one is how to tune bands to be selected in real time as number of bands varies. This paper presents an application to progressive band processing of anomaly detection, which can be carried out in a real time and progressive fashion with data updated recursively band by band in the same way that data is processed by a Kalman filter.

8871-25, Session 5

Quality control of satellite-derived sea surface temperature

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The individual satellite-derived SST datasets are usually blended together to provide a regular SST analysis with good quality and high resolution in oceanic and atmospheric researches. Data Quality Control (QC) is a preliminary requirement for blending Satellite SSTs. Satellite SST data quality is generally validated by in situ SST. However, in situ data are sparse and not available globally in near real time (NRT), especially in the China Seas and their adjacent seas (CSAS). This paper proposes a complementary quality control procedure, which use the Operational SST and Sea Ice Analysis (OSTIA) system's SST analysis as a reference standard (TR) to identify outliers in infrared Satellite SST (TS) in CSAS. Firstly, we apply a time evolution check. The pixel Ts must lie between SSTmin and SSTmax. The SSTmin and SSTmax are defined relative to TR of the previous 10 days. Secondly, we perform statistical analyses of the differences (ΔSST) between the TS and the TR of the previous day. Outliers are handled using robust statistics, and the Gaussian parameters are trended in time series to monitor SST products for stability and consistency. Finally, cross-check between infrared and microwave SST is also applied to removes the residual cloud and aerosol contaminated SSTs. After all these QC procedures are applied, most of the satellite SST outliers have effectively removed in NRT and the remaining observation errors are mainly due to diurnal variability, which should be focused on in the future study.

8871-26, Session 6

A fast forward/backward semi-blind channel estimation for MIMO STC-OFDM systems

Lena Chang, National Taiwan Ocean Univ. (Taiwan); Ching-Min Cheng, Chunghwa Telecom Co., Ltd. (Taiwan); Z. S. Tang, National Taiwan Ocean Univ. (Taiwan)

Recently, wireless communication techniques have been rapidly developed and it becomes essential to provide a communication system with higher capacity and faster transmission data rate. Multiple-input–multiple-output (MIMO) space-time-coding (STC) and orthogonal-frequency-division-multiplexing (OFDM) techniques are considered as the major techniques in the fourth-generation(4G) communications. It has been investigated that the combination of STC, OFDM and MIMO can provide a good performance for the multiuser scenarios with a small number of pilots.

In the study, we develop a fast subspace estimation for MIMO-STC-OFDM systems. We first analyze the symmetric structure of the correlation matrix corresponding to the received signals of MIMO-STC-OFDM systems. By utilizing the symmetric property, we proved that the forward-backward estimation (FBE) method which combines the forward and backward received signals can get a better estimation of sample correlation matrix and improve the accuracy of channel estimation. Then, we examined the structure of correlation matrix corresponding to the FBE and found the symmetric property of the associated eigenvector. Utilizing the property, we proposed the fast forward-backward estimation (FFB) method. The proposed FFB calculates the noise subspace of the correlation matrix by performing eigen-decomposition on two half-dimensionality matrices which obtained from the correlation matrix of FBE, individually. The FFB has the same performance as the FBE, but the computation complexity of FFB is one-fourth of FBE. Computer simulations demonstrate the effectiveness and accuracy in channel estimation of the proposed FFB which alleviates the computation complexity and improve the convergence rate of the existing semi-blind channel estimation methods based on subspace-decomposition.

8871-28, Session 6

Hyperspectral image compression and target detection using nonlinear principal component analysis

Qian Du, Wei Wei, Ben Ma, Nicolas H. Younan, Mississippi State Univ. (United States)

A hyperspectral image cube contains hundreds of correlated spectral bands. One approach of reducing its dimensionality is to transform the data onto a low-dimensional space. For instance, principal component analysis (PCA) is a commonly used approach. Because of atmospheric compensation and sensor-level degradation, there exists nonlinear correlation between different bands. Therefore, in addition to the widely used linear methods, the performance of nonlinear dimensionality reduction methods should be investigated.

Here, a nonlinear PCA (NLPCA) using auto-associative neural network is considered, which includes three layers: input, hidden, output. The numbers of neurons in the input and output layers are identical, equaling the number of original bands. The number of neurons in the hidden layer is much lower, resulting in data compression or dimensionality reduction. We compare its rate-distortion performance with PCA-based compression, which is comparable. However, in our research, the extracted principal components are used for target detection, which is of great interest in real application of hyperspectral remote sensing. The experimental results show that NLPCA can perform much better than the linear PCA in target detection or kernelized nonlinear detectors using the original data. Therefore, we integrate hyperspectral image compression and target detection in a unified fashion. To facilitate its practical application, the overall system is implemented in parallel using a graphics processing unit (GPU), which shows excellent speed-up performance.

8871-29, Session 6

A normal laser warning system model based on Hadamard transform

Liu Fei, Shao Xiaopeng, Han Pingli, Xidian Univ. (China); Chang Hong, Weihai Vocational College (China)

A normal laser warning system is designed as laser warning taking a great role in laser countermeasure, it is very important to extract useful information from weak laser signal with low signal to noise ratio (SNR) which is obtained in complex battlefield environment. Since the SNR of signal received by laser warning system is very low in real battlefield, the weak signal merging in heavy noise becomes too difficult to detect. Traditional signal processing methods to removal this kind of noise which is detected by laser warning system, that only mean filter or wiener filter are used; perform poorly in improving the SNR. A modified matrix Hadamard transform based on the weighting theory, overcame the disadvantages of matrices that are commonly used to cope with weak signal with low SNR. The modified matrix generating method of Hadamard transform is introduced in detail, and then theory analysis, calculations and simulations on the modified matrix Hadamard transform are presented. The SNR of signal increased about 7 times when using the modified matrix Hadamard transform to processed, so the other results showed that this kind of Hadamard transform performs excellently in increasing detection probability and decreasing False Alarm Ratio (FAR) of the laser warning system.

8871-30, Session PMon

Digital transceiver design for two-way AF-MIMO relay systems with imperfect CSI

Chia-Chang Hu, Yu-Fei Chou, Kui-He Chen, National Chung Cheng Univ. (Taiwan)

In the paper, combined optimization of the terminal precoders/equalizers and single-relay precoder is proposed for an amplify-and-forward (AF) multiple-input multiple-output (MIMO) two-way single-relay system with correlated channel uncertainties. Both terminal transceivers and relay precoding matrix are designed based on the minimum mean square error (MMSE) criterion when terminals are unable to erase completely self-interference due to imperfect correlated channel state information (CSI). This robust joint optimization problem of beamforming and precoding matrices under power constraints belongs to neither concave nor convex so that a nonlinear matrix-form conjugate gradient (MCG) algorithm is applied to explore local optimal solutions. Simulation results show that the robust transceiver design is able to overcome effectively the loss of bit-error-rate (BER) due to inclusion of correlated channel uncertainties and residual self-interference.

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8872-1, Session 1

Technology readiness levels and the Earth Venture Class Missions *(Keynote Presentation)*

George J. Komar, NASA Headquarters (United States)

NASA's Earth Venture (EV) class of missions are low-to-moderate cost Earth Science missions that include full orbital missions (EVF) and instruments for orbital missions of opportunity (EVI). As part of the Earth System Science Pathfinder (ESSP) program, these missions are designed to encourage the development of innovative approaches to Earth Science research by providing periodic, competitively selected opportunities to accommodate new and emergent scientific priorities. ESSP Projects are developmental, high-return Earth Science missions including advanced remote sensing instrument based missions. Due to the limited funding available for EV class missions, an increasingly common requirement is that the proposed instrument be at a Technology Readiness Level 6.

From space-borne instruments and components to data systems and modeling, the NASA Earth Science Technology Office (ESTO) funds and develops a broad range of technologies for the scientific observation and measurement of Earth. A key goal in the funding strategy of ESTO is to provide the resources needed to transition low TRL technologies to the TRL-6 level, thus enabling them to be used in EV class and other Earth Science missions.

The formal NASA definition of TRL-6: "System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application." provides high level guidance but is difficult to fully interpret without a detailed understanding of the platform on which the proposed instrument is to be based. At the proposal stage, the level of design detail needed for a full Technology Readiness Level evaluation is frequently not available. The goal of this presentation is to provide an ESTO perspective and begin a dialog on how proposers and reviewers for EV class missions might approach the TRL-6 requirement.

8872-2, Session 2

Approach to space-qualification of the ICESat-2 laser transmitter *(Invited Paper)*

Floyd E. Hovis, Nick W. Sawruk, Fibertek, Inc. (United States); Mark A. Stephen, NASA Goddard Space Flight Ctr. (United States); Joel Edelman, Slava Litvinovitch, Ryan Edwards, Joe Rudd, Jim Bautch, Elias Fakhoury, Fibertek, Inc. (United States)

A key element in the development of space-flight hardware is demonstrating the design meets the requirements of the intended mission. The areas of concern include an opto-mechanical structure that can survive the launch environment, a thermo-mechanical system that can adequately dissipate heat primarily through conduction and radiation, operational lifetimes in a vacuum environment that meet mission requirements with margin, and radiation hardness relative to the orbit of interest. NASA programs generally consider the design ready for flight when it is deemed to be at a Technology Readiness Level of 6 (TRL 6). A key component in the TRL-6 definition is a "prototyping demonstration in a relevant end-to-end environment". At the proposal and early hardware build phases the "relevant environment" is frequently not well defined, especially for the launch loads the hardware will experience.

The approach taken to defining the relevant environment for the ICESat-2 laser was to require that it be tested to the qualification levels defined in the General Environmental Verification Standard (GEVS, GSFC-STD-7000). The random vibration qualification levels in GEVS are high enough in both amplitude and frequency content (acceleration spectral density of 0.16 g2/Hz from 50 Hz to 800 Hz) to ensure that major resonances in the laser structure would be excited. Our approach to dealing with these high levels was to develop a flexure mounted design that filtered the high frequency content of the GEVS random vibration spectrum. In our talk we will discuss the program and system level implications of this design approach.

8872-3, Session 2

Space-qualification program for the laser diode module on the NASA ICESat-2 Mission

Nick W. Sawruk, Fibertek, Inc. (United States); Mark A. Stephen, NASA Goddard Space Flight Ctr. (United States); Kevin Bruce, nLIGHT Corp. (United States); Floyd E. Hovis, Fibertek, Inc. (United States)

A laser diode module (LDM) space qualification program was developed for the NASA Ice, Cloud and land Elevation Satellite-2, ICESat-2, mission. The ICESat-2 laser transmitter is a high performance diode-pumped solid state laser which requires high reliability, high efficiency and high brightness, fiber coupled laser diode modules. The test centric LDM space qualification program consists of several key phases including a technology plausibility study, component and module pedigree reviews, environmental acceptance and qualification testing, and extensive life testing. The intent of the plausibility study is to analytically and experimentally demonstrate the COTS module design is capable of being space-qualified. A pedigree review of the diode emitter population is conducted to screen out-of-family emitter from the population. The emitter pedigree review is a statistical analysis of several emitter performance metrics (efficiency, threshold current, etc.) with outliers being screened out. All completed modules undergo environmental acceptance testing including vibration, thermal cycling and an extended burn-in. The primary purpose of the acceptance testing is to surface internal workmanship issues. The pedigrees of the acceptance tested modules are subsequently reviewed in terms of the module performance data through the acceptance testing phase, with passing modules being certified as flight-qualified. A sub-set of the flight-qualified modules were exposed to environmental qualification testing and subsequently tested to failure to determine the LDM capability. Multiple units are being life tested and show no signs of degradation with run times approaching 20,000 hours. The details of the laser diode module space-qualification program are presented.

8872-4, Session 2

Development of a TRL-5 conductively cooled 2-micron laser for wind lidar

Timothy Shuman, Floyd E. Hovis, Fibertek, Inc. (United States); Upendra N. Singh, Mulugeta Petros, Jirong Yu, NASA Langley Research Ctr. (United States)

A coherent Doppler wind lidar system operating at 2 μm has the potential to be a key element of the 3-D Winds mission proposed in the NRC Decadal Survey of potential space-based earth science missions. The key performance parameters of the 2 μm laser transmitter needed for such a lidar system are: 250 mJ/pulse at 10 Hz; Pulsewidth > 100 ns and fully conductively cooled system. Under NASA Earth Science Technology Office (ESTO) funded Advanced Component Technology (ACT) Program, Fibertek and NASA Langley have been partnering to develop an engineering version of a Ho,Tm:LuLF based master oscillator/power amplifier (MOPA) that can be demonstrated by test to be at Technology Readiness Level 5 (TRL-5). Achieving TRL-5 has particular challenges for this technology due to its unique requirements. The cold operating temperature required to maximize the efficiency of the Ho,Tm:LuLF gain medium and the long resonator required to generate >100 ns pulsewidths make stabilizing the laser particularly challenging. At this time we have developed, thermally modeled and tested the required conductively cooled laser heads using heat pipe technology. We are in the process of finalizing the opto-mechanical design of the full laser system and will report on our progress in this area.

8872-5, Session 3

2-?m coherent lidar for CO2 and wind measurements *(Invited Paper)*

Shoken Ishii, Kohei Mizutani, Philippe Baron, Hironori Iwai, Toshikazu Itabe, National Institute of Information and Communications Technology (Japan); Hirotake Fukuoka, Hamamatsu Photonics K.K. (Japan); Takahiro Ishikawa, Nippon Aleph Corp. (Japan); Atsushi Sato, Kazuhiro Asai, Tohoku Institute of Technology (Japan)

The National Institute of Information and Communications Technology (NICT) has made efforts in order to develop a 2-?m coherent lidar for measuring CO2 concentration and line-of-sight (LOS) wind speed. A 2-?m conductively-cooled laser-diode-pumped single-frequency Q-switched solid-state laser was developed at the NICT. The 2-?m laser power of 2.4 W (80 mJ, 30 Hz) were obtained. A wavelength is set at 2051.250 nm for the LOS wind measurement and t wo wavelength (on- and off-line laser) are setting at 2051.250 nm and 2051.034 (2051.058) nm for the CO2 measurement. The two wavelengths correspond to the far-wing and wing of the R30 absorption line of CO2, respectively. Receiving components of the 2-?m coherent lidar are a Mersenne off-axis telescope with a 10-cm aperture, a two-axis scanner, two heterodyne detectors, fiber optics, and signal processing devices. Experimental wind measurements were carried out to evaluate the performance of wind profiling. The LOS wind measurements were made for ranges up to about 20 km. The wind speeds derived from the zero-wind-speed returns achieved a bias-free and high precision of 0.12 m/s. Experimental horizontal CO2 measurements were made to examine the detection sensitivity of the 2-?m coherent lidar in April and May, 2008, and October, 2009. Experimental vertical CO2 measurements were made for the Greenhouse gas Observing SATellite (GOSAT) data products validation in February 2010 and in January and February 2011. In the paper, we present overview of our 2-?m coherent lidar and experimental results.

8872-6, Session 3

Lab demonstration of the hybrid Doppler wind lidar (HDWL) transceiver

Catherine T. Marx, NASA Goddard Space Flight Ctr. (United States)

No Abstract Available

8872-7, Session 3

Two-component wind fields from scanning aerosol lidar and motion estimation algorithms

Shane D. Mayor, Pierre Dérian, Christopher Mauzey, Masaki Hamada, California State Univ., Chico (United States)

In 2007, the Raman-shifted Eye-safe Aerosol Lidar (REAL) was operated almost continuously for 3-months in Dixon, California, as part of the Canopy Horizontal Array Turbulence Study (CHATS). Two-component wind vectors were derived from the nearly-horizontal scans by applying a cross-correlation algorithm. The components of the vectors were compared with wind components measured by tower-mounted sonic anemometer at a range of 1.6 km from the lidar. Time series comparisons reveal the best correlation between the anemometer and lidar-derived velocities occurs at night when winds are light and the atmosphere tends to be stable. Stronger winds and turbulence, as typically occurs during the day, reduces the correlation between the two forms of measurement.

In late 2012, the CSU Chico lidar research group began implementing an entirely new method for deriving two-component wind vectors from the aerosol image sequences. The technique is known as “wavelet-based optical flow”. During the summer of 2013, we plan to compute wind vectors from the REAL data in real-time (using both cross-correlation and wavelet-based optical flow) and compare them with wind measurements from a nearby compact Doppler lidar. This work will be conducted in Chico, California, starting in early June. Therefore, new experimental results should be available for this presentation if all goes as planned.

In addition to the above, we are also generating synthetic aerosol images and synthetic wind fields and advecting the aerosol features by the synthetic wind field to develop a more comprehensive understanding of the behavior and performance of these algorithms.

8872-8, Session 4

Development of a pulsed 2-micron integrated path differential absorption lidar for CO2 measurement *(Invited Paper)*

Upendra N. Singh, Jirong Yu, Mulugeta Petros, NASA Langley Research Ctr. (United States); Karl D. Reithmaier, Science Systems and Applications, Inc. (United States)

A 2-micron pulsed, Integrated Path Differential Absorption (IPDA) lidar instrument for ground and airborne atmospheric CO2 concentration measurements via direct detection method is being developed at NASA Langley Research Center. This instrument will provide an alternate approach to measure atmospheric CO2 concentrations with significant advantages. A high energy pulsed approach provides high-precision measurement capability by having high signal-to-noise level and unambiguously eliminates the contamination from aerosols and clouds that can bias the IPDA measurement.

8872-9, Session 4

Efficient 1.6 micron laser source for methane DIAL

Timothy Shuman, Fibertek, Inc. (United States); Amin R. Nehrir, Syed Ismail, NASA Langley Research Ctr. (United States); Ralph L. Burnham, Fibertek, Inc. (United States); Johnathan W. Hair, NASA Langley Research Ctr. (United States)

Methane is a potent greenhouse gas that on a per molecule basis has a warming influence 72 times that of carbon dioxide over a 20 year horizon. Monitoring of the long term concentration changes of this environmentally important species could be accomplished by a combination of airborne and space-based differential absorption lidar (DIAL) systems operating in the 1.6 µm region. These DIAL systems require the development of a narrow-line laser source capable of being tuned to be on or off of a methane absorption line. We have developed the required narrow-line 1.6 µm laser using an efficient nonlinear conversion scheme. By combining a single-frequency 1064 nm pump source and a seeded KTP OPO, more than 5 mJ of 1.6 µm pulse energy is achieved with a conversion efficiency in excess of 20%. The measured linewidth of the resulting 1.6 µm output was <50 pm, limited by the optical spectrum analyzer used to perform the measurement. Tuning of the OPO output over a 400 pm range via tuning of the seed wavelength verified the ability of this OPO to operate on the two wavelengths required by a DIAL instrument. The next step in the development of this laser source for use in a fieldable methane DIAL system will be the development of a ruggedized version of the laser technology.

8872-10, Session 5

Recent improvements to the Raman-shifted eye-safe aerosol lidar (REAL) *(Invited Paper)*

Shane D. Mayor, California State Univ.,Chico (United States); Denton Scott, Anna Petrova-Mayor, California State Univ., Chico (United States); Bruce M. Morley, National Ctr. for Atmospheric Research (United States); Richard W. Wortley, Hextek Corp. (United States)

One potential application of the Raman-shifted Eye-safe Aerosol Lidar (REAL) is to conduct offshore wind energy assessments. The lidar could be deployed on terra firma near the shore and scan horizontally over the ocean to obtain image sequences of the moving aerosol distribution. Numerical motion estimation algorithms can be applied to the image sequences to derive the two-component vector wind field from the displacement of aerosol features from frame to frame. The technique has several advantages, of which the largest is likely the unique ability to measure two wind components from a single instrument. (Two components are necessary to determine wind speed.) However, to be viable, the instrument must operate stably for long periods of time and unattended in order to build offshore wind climatologies. This presentation will describe recent hardware and software improvements that were made to the original NSF/NCAR REAL in an effort to move toward that goal. The improvements include modifications to the transmitter component configuration, development of a control system, new high-performance beam steering unit mirrors, and integration of gravity-referenced tiltmeters to sense platform pitch and roll to <0.0001 degree.

8872-11, Session 5

CELiS (compact eyesafe lidar system): a portable 1.5 ?m elastic lidar system for rapid aerosol concentration measurement *(Invited Paper)*

Michael D. Wojcik, Space Dynamics Lab. (United States); Alan Bird, Jason Wooden, Utah State Univ. (United States)

CELiS (Compact Eyesafe Lidar System) is a tactical elastic lidar system commissioned by the Strategic Environmental Research and Development Program (SERDP) for the purpose of air quality environmental compliance issues surrounding the offroad use of wheeled and tracked vehicles. A complete CELiS instrument weighs less than 300 lbs., is less than 2 cubic meters in volume and uses 700 W of 120V AC power. CELiS has a working range of better than 2km and a range resolution of 5m. Results of field tests will be presented.

8872-12, Session 5

Airborne elastic lidar observation of gravity wave in stable arctic lower troposphere

Iwona S. Stachlewska, Karol Wolek, Jacek Kopec, Konrad Bajer, Univ. of Warsaw (Poland); Roland Neuber, Christoph Ritter, Alfred-Wegener-Institut für Polar- und Meeresforschung (Germany)

A gravity wave was captured in the signals of the Airborne Mobile Aerosol Lidar (AMALi) on 28 May 2004 during Arctic Study of Tropospheric Aerosols (ASTAR) campaign conducted on Svalbard. The airborne elastic-depolarization lidar took observations in the nadir-pointing configuration at 532nm (parallel and orthogonal) and 1064nm wavlengths just outside of Isfiord. The orographic gravity wave was discerned from the backscatter ratio profiles obtained along the flight path despite their very low values (1.2-1.55). The wave was present at an altitude of about 2175m, had an amplitude of about 150m and oscillation period of about 14min, and was spatially persistent for at least an hour. An approach to model this wave's propagation with altitude by using the software developed for clear-air turbulence (CAT) prediction in upper troposphere was facilitated. The vertical wind and temperature profiles were obtained from radiosoundings launched at Ny-Alesund (the AWIPEV Base) at the time close to the airborne measuerement. The gravity wave characteristics, estimated based on the AMALi backscatter ratio profiles and the radiosounding profiles, was applied to a modified version of Scorer's equations to determine the vertical variability of the wave amplitude. This amplitude profile can then supply information on CAT occurence in upper troposphere by using the new CAT predictor.

8872-13, Session 5

A new lidar equation for laser pulses backscattered from optically thick media such as clouds, dense aerosol plumes, sea ice, and turbid coastal water

Anthony B. Davis, California Institute of Technology (United States)

The base of boundary-layer stratus clouds can be so low that it is not detectable by a space-based millimeter radar due to insufficient vertical resolution, yet it is key to the atmosphere's thermodynamic profile, hence to climate dynamics. Moreover, the smallest amount of drizzle swamps the radar reflectivity, normally targeting droplets, which matter the most for the radiation budget and hydrological cycle. Aerosol remote sensing techniques, both active and passive, fail for dense plumes near sources: fires, volcanoes, dust storms, etc. Sea ice thickness is a key property that is hard to determine by any means. Laser bathymetry breaks down in highly turbid waters where the two-way transmitted pulse is all but extinguished by the opaque medium. All of these remote sensing challenges have, at least in principle, a common solution: multiple scattering lidar, both ground- and space-based, or airborne.

I will survey several field demonstrations and feasibility studies, published or not, that collectively show what opportunities open up when the conventional lidar equation (based on a single back-scattering and two-way transmission) is abandoned in favor of multiple-scattering solutions of the full time-dependent 3D radiative transfer problem for pulsed laser sources, a.k.a. space-time Green functions of optical media. Closed-form expressions derived in the asymptotic limit of small mean-free-paths (a.k.a. diffusion theory) are particularly useful for mining the highly-scattered returns for physical information content. That form of analysis will be applied to the above-listed problems in remote sensing of the environment, and technical implementation challenges will be discussed.

8872-14, Session 5

Profiling the optical parameters of the atmosphere with lidar: measurement or a simulation based on past observations?

Vladimir A. Kovalev, Cyle Wold, Alexander Petkov, Wei-Min Hao, U.S. Forest Service (United States)

The distortions of the inverted lidar signals can be caused by (i) the constant offset that remains in the backscatter signal after removing the background component, (ii) the multiplicative distortion component, which level is related with the lidar signal intensity, and (iii) the signal noise in the wide wavelength spectra; the latter includes low-frequency components, which do not obey common random-noise statistics. These distortions, even minor, may yield significant distortions in the retrieved outputs obtained by the inversion of the lidar signal. Implicit and explicit premises and assumptions required for any solution of the lidar equation are additional sources of the uncertainty in the inversion results. There is no reliable way for checking whether used assumptions are valid, therefore, the lidar signal inversion can yield significantly biased results.

As a result, instead some statistically mean profile of the atmospheric parameter of interest with the corresponding probability function, one obtains some qualitative estimate of the profile with unknown uncertainty, which depends on the validity of used assumptions. It means that lidar profiling is not a measurement but a result of some simulation based on past observations.

8872-15, Session 5

Advances in HgCdTe APD-based ladar technology and applications

Michael D. Jack, Justin Wehner, Tricia Veeder, William McKeag, Aaron M. Ramirez, Jinxue Wang, Raytheon Co. (United States)

No Abstract Available

8872-16, Session 5

The compact, high peak power pulse all fiber laser for the high-resolution 3D imaging LIDAR system

Cunxiao Gao, Shaolan Zhu, Linquan Niu, Li Feng, Haodong He, Zongying Cao, Xi'an Institute of Optics and Precision Mechanics (China)

??An all fiber laser with master-oscillator-power-amplifier (MOPA) configuration at 1064nm/1550nm for the high-resolution three-dimensional (3D) imaging light detection and ranging (LIDAR) system was reported. The laser of seed was the directed modulated diode laser output with the fiber pigtail which pulsewidth could be tuned form 1ns to 20ns and the repetition frequence could be tuned form 10kHz~1MHz, which peak power is about 20mW. The three or four stages all fiber amplifier was used to amplify the signal of the seeder, and the exceeded 100kW of the peak power (10W average power) at 30kHz and 2.5ns was obtained finally. The laser was fit for to be the light source of the high-resolution 3D imaging LIDAR system extraordinarily because of its narrow puslewdith, high repetition frequence, good beam mode and high stability. Using this all fiber laser in the high-resolution 3D imaging LIDAR system, the image resolution of 1024?1024 and the distance precision of ±1.5 cm was obtained at the imaging distance of 1km.

8872-17, Session 6

Development of an underwater fibers optic lidar for the characterization of sea water and ice properties *(Invited Paper)*

Gilles A. Roy, Pierre Mathieu, Defence Research and Development Canada, Valcartier (Canada); Xiaoying Cao, Consultant (Canada); Alain Cinq-Mars, Defence Research and Development Canada, Valcartier (Canada)

RDDC Valcartier has developed a unique underwater lidar for the measurement of different properties of sea water and ice. The lidar head is designed to go under water and consists of four telescopes that are connected to the detection and emission unit via five 42 m fused silica optical fibers. Three telescopes are used for data collections, while the forth is used for laser emission. The laser source and the detection unit are located on a surface vessel. The laser beam is injected into a 100 µm in diameter optical fiber. The collimation of the laser beam is done into the lidar head via a 25 mm in diameter 45 mm focal length lens; the laser beam is linearly polarized using a polarization beam splitter. A 50 mm receiving telescope co-aligned with the laser beam is used for linear depolarization measurements. A second 50 mm telescope is used to collect off-axis scattered light while a third 50 mm telescope is used to collect inelastic scattered radiation (raman and induced fluorescence signal).

The laser source and detection units are mounted on a small optical table for easy access/modification. Various laser sources and lidar detection techniques (Q switch pulses or frequency modulated) could be easily implemented. The lidar head can be deployed under water or mounted on a flying platform.

In this work, the lidar system will be described in details and preliminary results obtained with a Q-Switch, 532 nm, 1 ns pulse laser source will be presented and compared with the anticipated performance for different water bodies.

8872-18, Session 6

Rapid scan absorption spectroscopy for remote sensing at 1.6 um *(Invited Paper)*

David F. Plusquellic, Kevin O. Douglass, Stephen Maxwell, Joseph Hodges, David Long, Gar-wing Truong, James R. Whetstone, National Institute of Standards and Technology (United States)

A method to perform rapid step-scan absorption spectroscopy for remote sensing of greenhouse gases in the near-infrared wavelength range is presented. The method is based on a compact, fiber based diode laser system to perform scans over a bandwidth of 37.5 GHz, with a step size of 300 MHz and a scan rate of 40 kHz using a single 2nd order sideband from an electro-optic phase modulator driven by an arbitrary waveform generator. Single sideband selection is accomplished using a low finesse Fabry-Perot filter cavity with a finesse that is sufficiently high to give <2 % transmission of the diode frequency carrier and all other non-resonant sidebands while sufficiently low to ensure fast on-resonance switching times as short as 100 nsec. The diode laser is actively stabilized to the filter cavity to eliminate frequency drift of the cavity's transmission comb used for sideband selection and scanning. The method is first demonstrated in a 45 m long White cell for detection of carbon dioxide near 1602.4 nm and for methane near 1645.5 nm. Ambient level detection is demonstrated with a signal-to-noise ratio of ~5:1 over a path length of 45 m in a 5 ms integration time. The noise equivalent absorption is estimated at 5x10-9 cm-1 Hz-1/2 and the Allan variance is linear for measurement times ranging from 25 us to 1 sec. The scan speed, resolution and bandwidth are well suited for remote sensing using integrated path and differential absorption LIDAR techniques.

8872-20, Session 6

Enhancements to INO's broadband SWIR/MWIR spectroscopic lidar

Simon Lambert-Girard, Martin Allard, INO (Canada); Michel Piché, Ctr. d'optique, photonique et laser (Canada); François Babin, INO (Canada)

Recent advances in INO's broadband SWIR/MWIR spectroscopic lidar are presented. The system is designed for the detection of gaseous pollutants in air via active infrared DOAS. Two distinctive features are a broadband and tunable sub-nanosecond PPMgO:LN OPG and an in-house gated MCT-APD focal plane array. Recent measurements demonstrating a minimum sensitivity of 60ppm-m for methane will be described. Results of enhancements to the laser source using small or large bandwidth seeds indicate that the OPG output spectral energy density can have controllable spectral widths and stable spectral shape from pulse to pulse which will allow more sensitive measurements.

8872-21, Session 6

Development of a field-widened Michelson spectroscopic filter for a near-infrared high spectral resolution lidar

Dong Liu, Yongying Yang, Zhongtao Cheng, Hanlu Huang, Bo Zhang, Yibing Shen, Zhejiang Univ. (China)

High spectral resolution lidars (HSRLs) designed for aerosol and cloud remote sensing are increasingly being deployed on aircraft and called for on future space-based missions. Spectral discrimination between scattering from molecules and aerosols or cloud particles is the basis of the HSRL technique, and several lidar approaches have been developed to obtain this discrimination. Atomic and molecular absorption filters are robust, stable, and can achieve complete separation of Mie scattering (from aerosol or cloud particles) from Cabannes scattering(from molecules); however, absorption filters are lossy and gaseous absorption lines do not exist at many convenient laser wavelengths. Fabry-Perot interferometers are simple and can be tuned to any wavelength, but are limited by acceptance angle. Field-widened Michelson interferometer (FWMI) is considered to have the ability to overcome the deficiencies of the aforementioned filters as it can perform well at relatively large off-axis angles, is nearly lossless, and can be built to any wavelength. In this paper, the development process of an FWMI that is introduced to be the spectroscopic filter for a near-infrared HSRL instrument will be present. The selection of the free spectral range (FSR) of the FWMI, as well as the methods that are employed to obtain the object spectral transmission of the FWMI will be described in detail. Experiments on studying the characteristics of the FWMI will be given.

8872-30, Session 6

On independent lidar ratio retrieval from ceilometer signals

Iwona S. Stachlewska, Univ. of Warsaw (Poland); Christoph Ritter, Alfred-Wegener-Institut für Polar- und Meeresforschung (Germany); Matthias Wiegner, Ludwig-Maximilians-Univ. München (Germany)

We propose a method for retrieving profiles of lidar ratio from ceilometer observations conducted at two elevation angles of the laser beam, pointing into the atmosphere in the vertical and at the 5-20 deg from it. The two-angle evaluation approach is applied to obtain directly the aerosol optical thickness profile, and then the extinction coefficient profile. The vertical measurement signals are elaborated using a modified version of the forward lidar approach to obtain the backscatter coefficient profile. The lidar ratio profiles are calculated by division of the independently retrieved extinction profile with backscatter profile. Although the proposed technique is obviously limited to the atmospheric boundary layer, it is still a cost efficient approach to enhance the quality of deliverable of any simple elastic lidar and/or ceilometer.

8872-22, Session PMon

Analysis of the characters of chromophoric dissolved organic matter in water using laser induced fluorescence and spectral fluorescence signature

Peng Chen, Zhihua Mao, Haiqing Huang, The Second Institute of Oceanography, SOA (China)

A sort of analytical method of fast diagnosis of chromophoric dissolved matter (CDOM) in water is discussed. The total luminescence spectra (TLS) of CDOM in several types of water samples with laser-induced fluorescence (LIF) measurements using a 405 nm wavelength excitation source were measured in the laboratory, and the spectral characteristics of CDOM were analysed. The excitation light direction was perpendicular to the detector, in order that emission light was separated from excitation light. Two dichroic mirrors perpendicular to directions of excitation light and detectors were deployed to reflect the laser beams back to the measurement cell to increase the signal intensity. Background fluorescence was corrected by the way of subtractions between the signal with laser excitation and without laser excitation. The spectra of CDOM were pointed out and obtained with spectral fluorescence signature (SFS) technique, with the capability of detecting and identifying trace substances in a variety of targets in the presence of other, background matter responding to optical excitation with overlapping signals, where the CDOM fluorescence peak is typically located at 508nm and Raman scattering band, peaking at 471 nm, were detected with 405nm wavelength excitation. The spectrum of water Raman scattering and fluorescence of CDOM were separated from TLS with fitting Gaussian of the least squares method, and the curve of fluorescence peak intensity of CDOM against corresponding concentration of CDOM is showed. Correlation (R2=0.87) was observed between CDOM concentration and fluorescence, and a high correlation (R2=0.93) was obtained after fluorescence normalized to water Raman scattering. The results have demonstrated the utility of the LIF technique as an integrated tool for research and observations.

8872-23, Session PMon

Numerical model of the Doppler lidar network measurements in PBL

Evgeniya A. Shelekhova, Alexander P. Shelekhov, Institute for Monitoring of Climatic and Ecological Systems (Russian Federation)

In this paper the numerical model of the Doppler measurements for high horizontal spatial resolution using the scheme with lidar network are presented. It is assumed that the several Doppler lidars have different location in selected area. The selected area is divided by grid. The Doppler lidars measure the components of mean wind velocity in the points corresponding grid cells and the horizontal spatial resolution of the Doppler measurements is defined the grid sizes. We simulate the variances, which characterize the measurement uncertainty of components of mean wind velocity all lidars. It is shown that the variances are different for all lidars and depend strongly on state of the atmospheric turbulence and the number and sizes of grid cell. Also the variances are the complex functions of the signal-to-noise ratio, VAD sector scan angle, elevation angle, and direction sensing. The measurement uncertainty of mean wind velocity component can be significantly increased if we use the scheme with the Doppler lidar network at one and the same time.

For numerical simulation of atmospheric parameters we use the 1D model of homogeneous PBL model and "e-l" – turbulence model. Numerical simulation of the Doppler lidar measurements was calculated for meteorological conditions, which were observed at the Tomsk Bogashevo Airport (TOF), Russia for August, 2012. The initial meteorological data required for short prediction were taken from archive of website of the University of Wyoming (www.weather.uwyo.edu) and observation data from TOF. Measurement data of geostrophic wind, temperature, humidity, and other atmospheric parameters were obtained from weather station UNNN (www.weather.uwyo.edu), Meteorological Temperature Profiler MTP-5 (TOF) and Weather Transmitter WTX 520 (TOF).

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8872-24, Session PMon

Design of the field-widened Michelson spectroscopic filter for a high spectral resolution lidar

Hanlu Huang, Dong Liu, Yongying Yang, Zhongtao Cheng, Yibing Shen, Zhejiang Univ. (China)

Atmospheric aerosols play an important role in atmospheric physics, and a more accurate measurement has great research significance and social benefit. Lidars are an effective tool for the detection of the aerosols, among which the high spectral resolution lidars (HSRLs) have been given more and more attention for its robust calibration, simplified inversions without reliance on a priori assumptions. HSRL technique achieves accurate measurement by separating the Mie and Rayleigh scattering signals using the high-spectral-resolution spectroscopic filter. Filters like F-P interferometric filters and atomic/molecular absorption filters have limits while the field-widened Michelson interferometer (FWMI) stands out for large angular acceptance, high photon efficiency and flexibility to any laser wavelength. In this paper, an FWMI, which consists of a cubic beam splitter and two orthogonal arms, is introduced to be the spectroscopic filter of an HSRL. Applied as a filter for HSRL aerosol profiling, the FWMI is different from its compatriots in wind/temperature measurements that the optical path difference (OPD) varies very slowly (no more than approximately 1/20 of the laser wavelength) within the incident angle and environment temperature. The design procedure of the FWMI is described in detail and two different configurations (one is a solid arm combined with a pure air arm, and the other is a solid arm with an air-glass-mixed arm) are studied for comparison. A tolerance evaluation system is also established to assist the design process.

8872-25, Session PMon

Modeling of a field-widened Michelson interferometer for high spectral resolution lidar

Zhongtao Cheng, Dong Liu, Yongying Yang, Yibing Shen, Zhejiang Univ. (China)

High spectral resolution lidars (HSRL) have shown great advantages for the measurement of backscatter and extinction coefficients of aerosols and clouds due to its spectral discrimination process, which brings about more straightforward and accurate retrieval without a prior assumptions in contrast to standard backscatter lidars. To obtain this spectral discrimination, a field-widen Michelson interferometer (FWMI) is under development at Zhejiang University. The interferometer is composed of a cubic beam splitter, a solid arm and an air arm, and will be employed as the spectroscopic filter of an HSRL to block the aerosol signals but transmit the molecular backscattered photons optimally. The fabrication errors such as the defection of beam splitter coating and polarization, glass length deviation and surface imparallelism, imperfection of anti-reflection coating and so on, can degrade the performance of the spectroscopic filter. Moreover, the limitations from appliance conditions, for instance, photoelectric feedback error for PZT drive, the requirement of tilted placement, the temperature drift during operation, will also make the transmittance of interferometer deviate from designed values. A comprehensive radiometric model of the FWMI is developed, which incorporates all these practical imperfections indicated above. The model can be used to evaluate the machinery tolerance budgets for FWMI design and decide optimal state of usage for FWMI appliance. In this paper, the principle of the tilted FWMI as the spectroscopic fitler of the HSRL will be presented. The general theoretical method to estimate the transmittance characteristics of the FWMI will be expressed and the modeling process will be discussed in detail.

8872-26, Session PMon

Photon counting detector for satellite laser ranging with sub-picosecond timing stability

Josef Blazej, Ivan Prochazka, Czech Technical Univ. in Prague (Czech Republic); Jan Kodet, Czech Technical Univ. in Prague (Czech Republic) and Technische Univ. München (Germany)

The concept and preliminary experimental results of photon counting detector package based on a single photon avalanche diode with active gating and quenching circuit are presented. The single shot timing resolution of time-correlated photon counting experiment is about 30 ps, however demonstrated long-time stability allows averaging for both indoor and satellite laser ranging experiments. Two picosecond laser versions are employed as signal source – laser diode 43 ps at 778 nm, and fiber based laser 80 ps at 531 nm, used experiment repetition rate are from 500 Hz to 5 kHz. The NPET timing devices are used to register detection events and custom software and algorithm are used to process measured data. The long term delay stability sub-picosecond range and small temperature drifts of all elements of measuring chain are crucial to obtain useful data for final time scale comparison in picosecond range. The experimental results from measurement of long term stability of detector delays, delay independence on position in detector active area, and new achievements in quenching techniques will be presented. The detector is perspective for any remote sensing application based on single photon counting where long-term stability can be capitalized to achieve sub-picosecond timing resolution.

8872-27, Session PMon

ICESat-2 laser technology development

Ryan Edwards, Nick W. Sawruk, Floyd E. Hovis, Patrick Burns, Theodore Wysocki, Joe Rudd, Brooke Walters, Elias Fakhoury, Vincent Prisciandaro, Fibertek, Inc. (United States)

The NASA Ice, Cloud, and land Elevation (ICESat-2) mission incorporates a high spatial resolution laser altimeter instrument, Advanced Topographical Laser Altimeter System (ATLAS). Fibertek reports on the development of the enabling laser technology and the various architectures explored. The primary design driving requirements were an end-to-end wall-plug efficiency of >5%, temporal pulse widths of < 1.5ns, frequency tunable over 100pm, narrow spectral line width of < 12pm, pulse repetition frequency of 10kHz and diffraction limited beam quality. A 1µm master-oscillator power amplifier followed by a frequency doubler was chosen as the general design architecture. A linear, end-pumped oscillator was chosen for the design as it met all requirements and was based on mature technology. The amplifier architecture was end-pump Nd:YVO4 slabs, chosen for high efficiency and ability to preservation high beam quality. The end result of the 1µm MOPA was a 1.5mJ in a diffraction limited beam (M2<1.5), less than 1.5ns pulse width, and spectral width of <9pm. A single pass critically phased match LBO crystal was used as the frequency doubler due to, radiation hardness and high bulk damage thresholds. Typical frequency conversion efficiencies ranged between 67%-70%. The final system delivered diffraction limited, 1mJ, 1.3ns pulses, and spectral width of < 5pm at 532 nm and an overall optical-to-optical efficiency of 22%. This paper presents the laser design evolution, an overview of the final laser architecture and performance testing results.

8872-28, Session PMon

Quantitative measurement of ozone and ethylene in remote infrared (9-11 ?m) differential absorption lidar experiments

Taieb Gasmi, Saint Louis Univ.- Madrid Campus (Spain)

Ethylene and ozone behaviours show a high degree of coincidence. The two gases start to increase, reach a peak and then decay to a plateau, which lasts 3 hours. The net difference in ethylene concentration (Delta C2H4) versus that of ozone (Delta O3) is illustrated for successive days. (Delta O3) mimics to a good extent the behaviour of (Delta C2H4) which hence reveals a good relationship between the two gases. However it is well established that in the lower troposphere, especially in urban areas, chemical reactions of biogenic and anthropogenic VOC (Volatile Organic Compounds) and anthropogenic NOX emissions dominate over those of methane and its degradation products. Thus, it is widely accepted that tropospheric ozone results from the interaction of pollutant oxides of nitrogen and non-methane hydrocarbons with solar radiation leading ozone and carbonyl compounds which can further break down to produce additional O3. A key non-methane compound is the ethylene whose atmospheric chemistry is well studied. Basically, the role of this alkene is the efficient conversion of NO to NO2 and subsequently, the increase of tropospheric ozone.

So according to our basic photochemical smog model one should expect a direct correlation between the C2H4 evolution and that of O3 under similar meteorological conditions for the urban atmosphere and UVB radiation that prevailed during the days of the campaign. All these observation constitute additional evidence to the many models that state that ethylene, being a hydrocarbon, has a role to play in the generation of tropospheric ozone.

8873-36, Session PMon

Effects of wildfire smoke on atmospheric polarization

Joseph A. Shaw, Nathan J. Pust, Elizabeth Forbes, Montana State Univ. (United States)

An all-sky polarization imager was used to measure visible and near-infrared skylight polarization during a three-day period during which the sky was increasingly filled with smoke from a nearby wildfire. In-situ sensors were used to measure the aerosol size distribution, aerosol scattering coefficient, and aerosol extinction coefficient throughout this period. A solar radiometer also measured atmospheric extinction at multiple wavelengths. This presentation uses data from these sensors to show how the evolving aerosols strongly altered the skylight polarization.

8873-37, Session PMon

Photoelastic modulator non-idealities in magneto-optical polarization measurements

Stefaan Vandendriessche, Thierry Verbiest, Katholieke Univ. Leuven (Belgium)

Modifying and detecting the polarization of light is increasingly important in many contexts such as Faraday isolators and electro-optical modulators. In order to control the polarization of light, it is necessary to know the polarization characteristics of the materials used in the applications. To be able to (magneto-)optically characterize novel materials, we designed a setup using a single photoelastic modulator (PEM) to simultaneously detect natural and magnetic circular dichroism and circular birefringence over a large spectral range.

We then theoretically analyzed and experimentally characterized the effect of non-idealities in the PEM on the setup and the resulting data. Our results demonstrate an influence of PEM non-idealities on the measured signals, resulting in non-negligible mixing of circular birefringence and circular dichroism signals. Our measurements of the wavelength dependence of these non-idealities reveal larger non-idealities towards shorter wavelengths. These results illustrate the necessity to take PEM non-idealities into account when working with PEMs, especially at shorter wavelengths or when dealing with signals spanning different orders of magnitude. PEM non-idealities, while frequently neglected in experimental setup design and theoretical derivations, are expected to be more complicated and possibly exert a larger influence on obtained results for experimental setups with multiple PEMs.

8873-38, Session PMon

Polarization characteristics of dust aerosol particles

Zengzhou Hao, Delu Pan, Fang Gong, Haiqing Huang, The Second Institute of Oceanography, SOA (China)

Dust aerosol, which is an important natural aerosol, can affect environment by long-distance transport. Dust event is always heavy and covers large region. In this paper, to detect dust aerosol from satellite remote sensing, the phase matrix function of dust aerosol particles are calculated by using the Mie scattering theory and the lognormal distribution function to describe the dust particles size distribution. The polarization characteristics of dust aerosol particles during wavelength 0.2~40?m for solar radiation and earth-atmosphere long-wave radiation are studied at different relative humidity conditions. Some primary results show that, the scattered intensity has less effect by relative humidity and shows a trend of decreasing firstly and then increasing along with the increasing scattering angle, the increasing tendency decreases with the increasing wavelength; And for the linear and circular polarization of scattered radiation, the change with the scattering angle and relative humidity has difference properties at different band; In the forward and backward scattering directions, it only produces the circular polarization by dust aerosol particles, when assuming that incident light is right hand circularly polarized. Polarization properties of scattered light and their differences with humidity mainly change in the backward scattering region, where it is an arched form. The scattering angle for peak point is different at different relative humidity and the peak position drift to the larger scattering angle with the decreasing relative humidity. Those results are nice for detecting dust aerosol by polarization observations.

8873-39, Session PMon

Optical characterization of amber from Chiapas, Mexico

Guadalupe Lopez , Rafael Espinoza-Luna, Ctr. de Investigaciones en Óptica, A.C. (Mexico); Claudio Frausto-Reyes, Ctr. de Investigaciones en Óptica A.C. (Mexico)

An optical characterization of amber samples from México, the Baltic Sea and fake samples is presented, with the aim of discriminate between genuine and fake samples. We sought to identify the physical variables that could serve as the basis for the development of a device whose operation was able to discriminate between samples of genuine and fake amber.

The optical refractive index was determined by Spectroscopic Ellipsometry, Abbe refractometry, and by the Brewster angle. The Raman spectra and the fluorescence optical responses were also determined. The results obtained indicate that the refractive index is not a robust variable that can differentiate between genuine amber and a fake sample. On the other hand, the Raman spectra and the fluorescence responses provide information that allows discriminating between both types of samples. For this reason, we used the results obtained by fluorescence as a basis for the design and construction of a prototype simple, reliable, portable, and affordable for authentication of the Mexican amber.

8873-40, Session PMon

A compact and robust method for spectropolarimetry

William B. Sparks, Space Telescope Science Institute (United States)

Motivated by astrobiological remote sensing needs, Sparks et al (2012 Applied Optics 51, 5495 “A compact and robust method for full Stokes spectropolarimetry” present an approach to spectropolarimetry which offers the prospect of high sensitivity over a very wide wavelength range (UV, optical, IR). Using static, robust components the polarization information is encoded onto one dimension of a two-dimensional data array, while the other dimension records the spectrum. A spatially varying retardance along the spectrograph slit, followed by a polarization analyzer, encodes the Stokes parameters as coefficients of orthogonal trigonometric functions perpendicular to the spectrum. No moving parts are required and all polarimetric information is available on a single data frame, hence the technique is immune to time dependencies, free of fragile modulating components, has the potential for high sensitivity and offers a wide wavelength range with full Stokes spectropolarimetry. Within the Solar System, spectropolarimetry offers diagnostics for dust (cometary, zodiacal, rings), surfaces (rocky, regolith, icy), aerosols (clouds, dust storms) and high energy plasma emission processes. Beyond the Solar System, space-based telescopic spectropolarimetry has important contributions to make in the detection of extrasolar planets and their characterization. There are astrobiological applications for full Stokes polarimetry stemming from the interaction of light with chiral living organisms, which offers the potential for a remote sensing detection capability for microbial life.

8873-41, Session PMon

Orientational tomography of optical axes directions distributions of multilayer biological tissues birefringent polycrystalline networks

Natalia I. Zabolotna, Rostyslav Y. Dovhaliuk, Vinnytsia National Technical Univ. (Ukraine)

We propose a modified structure of polarimetry setup and a novel method to analyze measured distribution of optical axes` orientation in optically thin layer of histological section of muscle tissue.

Our polarimetry setup consists of a semiconductor laser, quarter-wave plate, collimator optics, polarizer and analyzer, micro objective, object of investigation and a CCD camera connected to the computer. The principal difference of our method from other well-known methods lies in direct approach for measuring the direction of optical axis of polycrystalline networks` biological crystals. To obtain such data, the simultaneous rotation of the analyzer and polarizer is performed during the process of measurement.

According to developed methodology to determine whether the particular biological tissue`s slice can be classified as "healthy" or "pathological" one need to evaluate several parameters. They include statistical, correlational and spectral moments of previously measured distribution of optical axes` orientation in polycrystalline network.

To test the validity of proposed method the distribution of optical axes` orientation in optically thin layer of histological section of muscle tissue was measured using previously described polarimetry setup with a 2-3% error.

Our results show that the biggest difference between healthy and pathological muscle tissue slices` values of statistical, correlational and spectral moments exists in case of 2nd, 3rd and 4th statistical moments (difference from 2.5-3 to 3.4-5 times), 2nd and 4th correlational moments (difference 2 times for the 2nd moment and 6 times for the 4th one) and 2nd and 3rd spectral moments (difference up to 2.5 times).

8873-42, Session PMon

A portable imaging Mueller matrix polarimeter based on a hybrid modulation approach

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Imaging polarimeters have been largely used for remote sensing tasks, and most imaging polarimeters are division of time or division of space Stokes polarimeters. Imaging Mueller matrix polarimeters have just begun to be constructed which can take data quickly enough to be useful. We have designed a full Mueller matrix polarimeter utilizing a hybrid modulation approach (modulated in both time and space) based on a micro-polarizer array camera and rotating retarders. We present this hybrid approach and various reconstruction schemes tailored to specific constraints. We also analyze the trade space, consisting primarily of trade offs between aliasing and noise/signal (SNR), speed of acquisition, and the number of reconstructible Mueller elements. Finally we present example data acquired with the instrument and some specific examples of reconstruction of that data.

8873-43, Session PMon

Analyzing vector diversification

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Condition Number (CN) and Equally Weighted Variance (EWV) have been shown to be the proper metrics of optimization in order to yield Stokes polarimeters with highest SNR under the assumption of independent and identically distributed noise. However, when that assumption is lifted and more than four measurements are made, it is possible to have designs that indicate an optimal CN and EWV, yet result in performance that is less than maximum attainable. As the number of measurements is increased, so is the dimensionality in which the four vectors of the reconstruction matrix lie. As a result, it is easier to find solutions where those four vectors are orthogonal, thus leading to CN and EWV being overly collapsed in the sense that there exists a huge plateau of optimal results and the distinction of the system's ability to handle other types of noises is not considered. Having a diverse set of measurements will improve the reconstruction in those cases. We present several possible metrics which add the measure of diversity into the design process.

8873-45, Session PMon

CALIOP receiver transient response study

Xiaomei Lu, Yongxiang Hu, Zhaoyan Liu, Shan Zeng, Charles R Trepte, NASA Langley Research Ctr. (United States)

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), an instrument on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), operated as an atmospheric lidar system to study the climate impact of clouds and aerosols in the atmosphere. This paper discusses the receiver transient response of the CALIOP instrument. A simple numerical model of the receiver transient response is presented, which predicts the relationship among the surface return signals at three range bins. The CALIOP transient response function in 30 m vertical resolution, which is used to remove any impacts on the attenuated backscatter profile of water clouds imparted by a non-ideal transient response of photomultiplier tubes (PMT), was obtained by using twelve adjacent lidar bins of land surface return. An analytical expression of the CALIOP transient response function in high vertical resolution, which is useful for the lidar altimetry study from the CALIOP lidar measurements, was calculated by the least square fitting of lidar measurements from land surfaces.

8873-1, Session 1

Infrared wire grid polarizers: metrology and modeling

Matthew C. George, Jonathon Bergquist, Rumyana Petrova, Bin Wang, Eric W. Gardner, MOXTEK, Inc. (United States)

The wire grid polarizer (WGP) remains one of the most useful optical components in the field. Benefits of the WGP over competing designs include a small form factor, broadband performance, large acceptance angle, and improved durability over organic polarizers. The WGP typically consists of an array of metallic lines with sub-wavelength pitch supported by a transparent substrate. Using our aluminum nanowire, large area patterning capabilities, Moxtek has developed high contrast wire grid polarizers on AR-coated silicon suitable for narrow and broadband applications in the MWIR and LWIR. Accurate metrology was gathered in both transmission and reflection from the SWIR to LWIR using a combination of FTIR and dispersive spectrometers, as well as laser-based light sources. The WGP structures were analyzed using SEM, FIB, and STEM techniques and optical data was derived from IR VASE, transmission, and reflectance measurements. Modeling of device performance was achieved using rigorous coupled wave analysis. Our 144 nm pitch broadband MWIR polarizer transmits better than 95% of the passing state while maintaining a contrast ratio of better than 33dB from 3.3-5.7 microns. Between 7 and 15 microns, our LWIR polarizer transmits better than 70% of the passing polarization state and has a contrast ratio better than 40dB. A narrowband AR-coated WGP for 7.5 micron wavelength transmits better than 94% of the passing state while maintaining a contrast ratio of better than 42dB. Narrow band antireflection-coated wafers for 10.6 micron laser line applications will also be presented. Laser damage thresholds and various damage mechanisms will be presented.

8873-2, Session 1

Assessing consistency of a Mueller matrix measurement by rotation of the sample under test

Thomas A. Germer, National Institute of Standards and Technology (United States)

It is a difficult task to assess the accuracy of measurements obtained by a Mueller matrix polarimeter. In some cases, one can test the behavior under specific conditions, for example, by measuring in the absence of a sample, by measuring the reflection of an isotropic surface, or by measuring the transmittance through a high quality polarizer. However, these ideal materials only test a small subset of the space spanned by all Mueller matrices. Worse yet, they often are part of the procedure used to calibrate the polarimeter, and thus, the polarimeter may be optimized for these polarizations. In this paper, we will present a method which spans a much wider set of Mueller matrices and may give a more realistic indication of systematic uncertainties. The method is based upon the rotational properties of a Mueller matrix. A relatively arbitrary, uniform object, created by stacking a few polarimetric elements together with intentionally misaligned axes, is placed in the polarimeter in a precision rotation stage. The Mueller matrix is then measured as a function of sample rotation. The values of the Mueller matrix elements, with the exception of the corner elements, will thus span a large range. However, they can each be transformed by matrix rotation back into the Mueller matrix at zero angle. The consistency between these resulting matrices is then taken as an indication of the measurement uncertainties. The method is demonstrated with measurements of several different samples.

8873-3, Session 1

Single-angle-of-incidence single-element rotating-polarizer (Single SERP) ellipsometer for film-substrate systems

A. R. M. Zaghloul, Cairo Univ. (Egypt)

The single-element rotating-polarizer ellipsometer is where a rotating polarizer is inserted into the incident beam and the reflected-signal intensity is detected using a photodetector. The polarizer is either rotated mechanically or electromagnetically. The angle of incidence of the beam is adjusted to detect the angles where the detector signal is dc. The ellipsometric function of the film-substrate system under measurement is of a unity magnitude at those detected angle(s). The number of required measurements (such angles of incidence) is related (directly proportional) to the number of system parameters to be determined: film thickness is one parameter, film refractive index is two parameters, and substrate refractive index is two parameters. The more parameters to be determined, the more the number of measurements required. This creates film-thickness bands, which number and width depend on the system physical properties and the wavelength used for measurement, and where a continuum exists above a certain film-thickness value. Accordingly, full characterization of film-substrate systems is limited to systems with large film thicknesses for the required multiple angles of incidence to exist. In this paper, we use only one detected angle of incidence to fully characterize the film-substrate system. This allows for film-substrate systems with much smaller film thicknesses to be fully characterized. A fast genetic algorithm is used to heuristically obtain all the system parameters: film thickness and refractive indices of the film and the substrate, or any subset thereof.

8873-4, Session 1

Real-time combined reflection and transmission ellipsometry for film-substrate systems

M. Elshazly-Zaghloul, Cairo Univ. (Egypt)

Combined reflection and transmission ellipsometry of film-substrate systems provides a wealth of experimental information that proves helpful with extracting the system parameters. In such a technique, both the reflection and transmission ellipsometric functions are simultaneously measured. The technique itself requires a special design of the sample for fixed and for multiple angles of incidence measurements. The data reduction could be done using numerical methods which are tedious and time consuming resulting in an overall slower technique. A closed-form inversion of the system parameters (film thickness, film refractive index, and substrate refractive index) would render a fast technique that is suitable for real-time applications. The sample used is a three-film-thickness sample and measurements are carried out at two angles of incidence. Real simple closed-form equations are derived through successive transformations and algebraic manipulations to obtain the refractive indices of the film and the substrate, in addition to the film thickness. A simple software program, with a limited number of code lines, is developed and tested yielding perfect results.

8873-5, Session 1

Evaluation of calibration methods for visible-spectrum division-of-focal-plane polarimeters

Samuel B. Powell, Washington Univ. in St. Louis (United States)

Recent advances in nanofabrication have facilitated the introduction of visible-spectrum division-of-focal-plane polarimeters. These sensors are made by integrating nanowire polarization filters directly with an imaging array. Size variations of the nanowires due to fabrication can cause the optical properties of the filters to vary up to 20% across the imaging array. If left unchecked, these variations introduce significant errors when reconstructing the polarization image. Calibration methods offer a means to correct these errors. This work compares two calibration methods: applying a single gain and offset per pixel versus multiplying the division-of-focal-plane “super-pixel” by a single matrix. The two methods are compared both quantitatively while varying illumination intensity, wavelength, angle, and degree of linear polarization; and qualitatively using data collected in the field.

8873-6, Session 2

Mathematical tools for the analysis and exploitation of polarimetric measurements *(Invited Paper)*

Jose J. Gil Perez, Univ. de Zaragoza (Spain)

The measured Mueller matrices contain until sixteen independent parameters for each measurement configuration (spectral profile of the wave probe of the polarimeter, angle of incidence, observation direction...) and for each spatially resolved element of the sample (imaging polarimetry). Thus, the polarimetric techniques are widely used for the study of a great variety of material samples in optics and remote sensing. Nevertheless, the relevant physical information does not appear explicitly in the measured parameters and thus the best knowledge of the structure of the physical information contained in a Mueller matrix is required in order to develop appropriate procedures for the polarimetric analysis. In this paper, the physically invariant polarimetric quantities are identified and decoupled, and the main approaches for serial and parallel decompositions of measured Mueller matrices into simple components are reviewed.

8873-7, Session 2

Partial Mueller matrix polarimeter design

Andrey Alenin, J. Scott Tyo, College of Optical Sciences, The Univ. of Arizona (United States)

Partial Mueller Matrix Polarimeters (pMMPs) are active sensing instruments that evaluate the scattering process by controlling both the generator and the analyzer states. Through a careful selection of those states it is possible to probe a subset of the Mueller matrix, thereby creating a partial measurement. In this paper we consider the structure of the Mueller and the measurement matrices by performing an SVD decomposition and investigating the possible arrangements of constituent orthogonal vectors/channels that the instrument supports. Limitations placed by the Mueller space are critical to understand when linear combinations of Mueller elements are part of the same column space-vector. The analysis is necessary in order to construct an instrument that takes a limited number of measurements to determine features of the Mueller object that prior analysis determined to be the most crucial for the task at hand.

8873-8, Session 2

3D radiative transfer effects in multi-angle/ multispectral radio-polarimetric signals from a mixture of clouds and aerosols viewed by a non-imaging sensor

Anthony B. Davis, Michael J. Garay, Jet Propulsion Lab. (United States); Feng Xu, Jet Propulsion Lab. (United States) and Joint Institute for Regional Earth System Science and Engineering (United States); Zheng Qu, Jet Propulsion Lab. (United States) and Raytheon Co. (United States); Claudia Emde, Ludwig-Maximilians-Univ. München (Germany)

It is widely believed that adding polarimetry to multi-angle spectrometric observations of aerosols will lead to vastly improved assays of their columnar burden and characterizations of their microphysics. Even when clouds are present, they have such different polarization signatures than aerosols that they may be essentially removed from the signal, thus exposing only those aerosols that are interacting with the clouds (and these are very high-value targets for climate scientists).

We put this last hypothesis to test using high-fidelity Monte Carlo 3D vector radiative transfer (vRT) simulations of a field of cumulus clouds embedded in more or less aerosol. These synthetic signals are compared with predictions based on an advanced linear mixing model. This idealized forward model uses an areal average of as many sub-pixel elements (each treated with 1D vRT) as are necessary to describe the aerosol- and Rayleigh-scattering atmosphere, assumed horizontally uniform, and the known cloud liquid water content field. We find that the 1D vRT cannot capture the polarization signal properly in the key angular region that contains the cloud bow, at least when there is a significant amount of aerosol. More surprising is that this is true even in limit of single scattering. However, since single scattering can be computed efficiently, even in 3D geometry, this last finding leads to some ideas about how to mitigate the inherently 3D vRT effects, and thus restore to some extent the desired aerosol remote sensing capability of the non-imaging sensor using only information from simple context cameras.

8873-44, Session 2

Measurement and modeling of mirror reflectance spectrum of polarized light in the UV band

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Ellipsometry is a well-known and relevant technique that has been used extensively to study specular reflection and transmission properties from surfaces and coatings. With the development of multi-band target detection, the requirement of the measurement in the multi-band is necessary to analysis the scattering properties of a target. The reflect light of a surface contains many features of a surface, which is usually used as a powerful tool for process in situ or ex suit monitoring.

But lots of paper discussed the measurement or model method by using ellipsometry in the visible to infrared band. Few references discuss about the measurement results of the surface in the ultraviolet band. As there has been increasing interest in the study of scattering and reflective properties in ultraviolet band. Researches on the scattering properties in the UV band are necessary.

In this paper, scatter measurements of some typical smooth samples in the UV band are performed by using the ellipsometry WVASE 32 made by J. A. Woolam Co. Inc. The polarized mirror-direction reflectance spectrum measurement results obtained are analyzed and compared. A reflectance spectrum model of the smooth material for polarized light in UV band was proposed. To explore the correctness of the model, we compared it with five-parameter BRDF model.

And these kinds of researches about measuring and analyzing of typical roughness samples in ultraviolet band have significant meanings in a lot of related fields.

8873-9, Session 3

Airborne multiangle spectropolarimetric imager (AirMSPI) observations over California during NASA's Polarimeter Definition Experiment (PODEX) *(Invited Paper)*

David J. Diner, Michael J. Garay, Olga V. Kalashnikova, Brian E. Rheingans, Sven Geier, Michael A. Bull, Veljko M. Jovanovic, Jet Propulsion Lab. (United States); Feng Xu, Jet Propulsion Lab. (United States) and Univ. of California, Los Angeles (United States); Carol J. Bruegge, Jet Propulsion Lab. (United States); Ab Davis, Univ. of Texas (United States); Karlton Crabtree, Russell A. Chipman, College of Optical Sciences, The Univ. of Arizona (United States)

The Airborne Multiangle SpectroPolarimetric Imager (AirMSPI) is an ultraviolet/visible/near-infrared pushbroom camera mounted on a single-axis gimbal to acquire multiangle imagery over a ±67° along-track range. The instrument flies aboard NASA's high-altitude ER-2 aircraft, and acquires Earth imagery with ~10 m spatial resolution across an 11-km wide swath. Radiance data are obtained in eight spectral bands (355, 380, 445, 470, 555, 660, 865, 935 nm). Dual photoelastic modulators (PEMs), achromatic quarter-wave plates, and wire-grid polarizers also enable imagery of the linear polarization Stokes components Q and U at 470, 660, and 865 nm. Example data acquired over California during January-February 2013 as part of NASA's Polarimeter Definition Experiment (PODEX), a field campaign designed to refine requirements for the future Aerosol-Cloud-Ecosystem (ACE) satellite mission, will be shown. Observations of aerosols, low- and mid-level cloud fields, cirrus, aircraft contrails, and clear skies were obtained over the San Joaquin Valley and the Pacific Ocean during PODEX. Analyses of radiance and polarization imagery are presented to illustrate instrument sensitivity to aerosol optical depths and microphysical properties, 3-D cloud morphologies and droplet size distributions, and bidirectional intensity and polarized reflectance factors for a variety of land and ocean surface targets.

8873-10, Session 3

Influence of polarization phenomenology on material discriminability using multi-view polarimetric imagery

Chabitha Devaraj, South Dakota State Univ. (United States); Michael Gartley, John R. Schott, Rochester Institute of Technology (United States)

In addition to spectral information acquired by traditional multi/hyperspectral systems, passive electro optical and infrared polarimetric systems also measure the polarization response of different materials in the scene. Such an imaging modality offers a complete optical description of a surface that can be utilized in identifying objects with complex morphological and camouflaged structures. The polarization property of the radiation from a remotely sensed surface, however, depends on the observation geometry of the system. Therefore, acquiring a polarimetric image in a single viewing direction is not sufficient to improve the material discriminability in the absence of a priori knowledge about the object geometry. Hence, this paper presents a novel multi-view polarimetric system for improving the target-background discriminability. The proposed system takes the approach of imaging the scene in three different viewing directions to infer the physical characteristics of the observed surface by utilizing the angular variation in the polarization response. The sensitivity analysis of the proposed polarimetric system that relates target-background discriminability to various scene related parameters indicates the imaging conditions under which the material discriminability is maximized. Furthermore, scenarios where polarization information can be very useful in improving the target contrast are identified by comparing the detection performance of the proposed system to that of a multispectral system.

8873-11, Session 3

How clear-sky polarization varies with wavelength in the visible and near infrared

Nathan J. Pust, Joseph A. Shaw, Montana State Univ. (United States)

Questions frequently arise as to how the clear-sky polarization pattern varies with wavelength. In the visible and near-infrared portion of the spectrum, it is sometimes erroneously believed that the degree of polarization (DoP) varies as inverse wavelength to the fourth power, as does the Rayleigh-scattered skylight. However, the real answer is much more complex. For example, in conditions with very low aerosol content, approaching the Rayleigh scattering limit, the DoP actually tends to increase slowly with wavelength throughout the visible spectrum. Even more importantly, the DoP spectrum can take on strong spectral features that are driven by similar spectral features in the underlying surface reflectance. This presentation will use a combination of measurements and simulations to illustrate and explain widely varying examples of clear-sky polarization spectra in the visible and near-infrared spectral region. One important conclusion of this study is that simple models which do not incorporate accurate aerosol and surface information have limited utility for simulating or predicting clear-sky polarization.

8873-12, Session 4

Mueller matrix microscopy *(Invited Paper)*

Mircea Mujat, R. Daniel Ferguson, Nicusor Iftimia, Physical Sciences Inc. (United States)

Polarization is a fundamental property of light and its measurement is one of the effective means of investigating the light-matter interaction. Polarization imaging provides additional contrast mechanisms as compared to traditional intensity imaging, without having to stain or label the sample. The most complete spatial polarimetric characterization of biological tissue is provided by Mueller matrix imaging. In addition to the classical intensity image, the Mueller matrix contains information on birefringent, dichroic or depolarization properties of tissue. Subsequently, these properties could be used to differentiate between normal and diseased tissue with the purpose of non-invasive optical diagnosis or for imaging microscopic structures relevant for both material science and biomedical research and to illustrate anisotropies not visible in the regular microscopy images. We describe here a new imaging technique, Mueller matrix microscopy, for investigating the anisotropic properties of the refractive index in biological samples. The system's capabilities are demonstrated first on mica, quartz and biological samples. Current polarization microscopes are working in transmission through transparent samples and in general measuring only in orthogonal polarization channel or doing partial polarization measurements. We have developed a polarization microscope capable of performing complete Mueller matrix imaging in both transmission and reflection configuration and at different wavelengths. Polarimetric microscopy can provide unprecedented details in biophysical measurement of cell functions, in analyzing the effects of electric or magnetic fields, photoactivation, testing of drugs or biocompatible polymers on live tissue, or in longitudinal studies on interacting cellular structures during cell division, motility and apoptosis.

8873-13, Session 4

Extraction of the inclination angle of nerve fibers in the human brain with 3D-polarized light imaging

Julia Reckfort, Hendrik Wiese, Melanie Dohmen, David Graessel, Forschungszentrum Jülich GmbH (Germany); Uwe Pietrzyk, Forschungszentrum Jülich GmbH (Germany) and Bergische Univ. Wuppertal (Germany); Karl Zilles, Forschungszentrum Jülich GmbH (Germany); Katrin Amunts, Forschungszentrum Jülich GmbH (Germany) and Heinrich-Heine-Univ. Duesseldorf (Germany); Markus Axer, Forschungszentrum Jülich GmbH (Germany)

Recently, the neuroimaging technique 3D-polarized light imaging (3D-PLI) has opened up new avenues to study the complex nerve fiber architecture of the human brain at unprecedented spatial resolution. This polarimetry technique is applicable to histological sections of postmortem brains utilizing the birefringence of nerve fibers caused by the regular arrangement of lipids and proteins in the myelin sheaths surrounding axons. 3D-PLI provides a three-dimensional description of the anatomical wiring scheme defined by the in-section direction angle and the out-of-section inclination angle. To date, 3D-PLI is the only available method that allows bridging the microscopic and the macroscopic description of the fiber architecture of the human brain.

Here we introduce a new approach to retrieve the inclination angle of the fibers independently of the properties of the used polarimeters. This is relevant since the image resolution and the signal transmission influence the measured birefringent signal (retardation) significantly. The image resolutions were determined using the USAF-1951 testchart applying the Rayleigh criterion. The signal transmissions were measured by elliptical polarizers applying the Michelson contrast.

Based on these results, a modified retardation-inclination-conversion function was proposed to extract the fiber inclination. The improvement of the extraction of inclination angle was verified using sections of the optic tract cut under different angles. The optic tract, composed of homogeneously oriented fiber, was chosen as a biological reference sample. The comparison of the actual and the inclination angles calculated with the theoretically proposed and the new modified function reveals significant improvement in the extraction of the fiber inclination.

8873-14, Session 4

Polarization-components techniques for NDE of composite heat damage

Brian G. Hoover, David E. Taliaferro, Virgil Kohlhepp III, Advanced Optical Technologies (United States)

Active/laser polarization-components techniques (PCT) is applied to non-destructive evaluation (NDE) of heat damage in aircraft-grade carbon-fiber bismaleimide (CF-BMI) composites. Polarization signatures of CF-BMI coupons subjected to various temperatures in a cone calorimeter are measured by a laboratory DRR laser polarimeter at visible wavelength. Machine-learning algorithms are trained on the polarimeter data to define PCT channels invariant over composite orientation and probe incident angle, and a classifier is applied to demonstrate the sensitivity and resolution of PCT NDE compared to conventional destructive damage-evaluation methods including Shore D surface hardness and residual mechanical strength in 3-point-bend tests. Background on heat damage in fiber composites and phenomenological mechanisms for the observed polarization signatures are also discussed.

8873-15, Session 4

LWIR polarization sensing: investigation of liquids and solids with MoDDIFS

Gilles Fortin, AEREX avionique inc. (Canada); Jean-Marc Thériault, Defence Research and Development Canada, Valcartier (Canada); Paul Lacasse, AEREX avionique inc. (Canada)

MoDDIFS (Multi-option Differential Detection and Imaging Fourier Spectrometer) is a DRDC Valcartier technology built around a differential Fourier Transform Infrared (FTIR) spectrometer optimized for optical subtraction in the long wave infrared (LWIR). MoDDIFS is a dual use hyperspectral prototype offering two fore-optics configurations: a long range fore-optics, specialized for the detection of small quantities of gaseous substances, and a polarization fore-optics, built to investigate liquids and powders spills. We report and present a preliminary analysis of a series of measurement tests made with the latter (polarization) configuration of MoDDIFS. The tests were performed under indoor and outdoor environments. Different liquid and solid substances were deposited on up to twelve different types of surfaces. Many liquid targets and some solid materials produce a noticeable linearly-polarized signal, with a more or less characteristic spectral modulation. For the liquids, the behavior of the observed radiance spectrum seems more predictable when the liquid is thick, or when it is deposited at any thickness on non-absorbing and weakly-reflective substrates. The behavior of the radiance spectrum observed becomes more complex when a thin layer of the liquid is deposited on a smooth and strongly-reflective substrate, or on an absorbing substrate. Polarized hyperspectral radiance measurements bring additional information on both targets and the backrounds as compared to standard unpolarized hyperspectral measurements, as long as the signal acquired is noticeably polarized. The tests performed can then help determine the materials for which the detection and the identification will be improved with polarized measurements.

8873-16, Session 4

Using linear polarization for LWIR hyperspectral sensing of liquid contaminants

Jean-Marc Thériault, Defence Research and Development Canada, Valcartier (Canada); Gilles Fortin, Paul Lacasse, AEREX avionique inc. (Canada); François Bouffard, Hugo Lavoie, Defence Research and Development Canada, Valcartier (Canada)

Passive Fourier-transform spectrometry can be used to remotely detect and identify liquid surface contaminants in the long wave infrared (LWIR). To be fully efficient, current passive FTIR techniques would greatly benefit from a significant improvement in signal-to-clutter ratio. Hyperspectral polarization sensing is seen as an approach with great potential to significantly improve the remote detection and identification of liquid contaminants. DRDC Valcartier recently initiated the development and field-validation of the novel imaging FTIR sensor MoDDIFS (Multi-option Differential Detection and Imaging Fourier Spectrometer) to address this issue. The primary focus of our study is to address the passive standoff detection of liquid contaminants by exploiting their polarization attributes. The MoDDIFS hyperspectral instrument has a unique capability to probe the horizontal and vertical polarization components of a scene in direct and differential modes. This paper reviews recent results obtained with MoDDIFS. Field measurements of polarized spectral radiance done on liquid contaminant simulants (Ethylene Glycol and SF96) probed at distances of 12 meters and 450 meters have been used to develop and test a GLRT-type algorithm adapted for liquid contaminants. The hyperspectral measurements and GLRT detection results are analyzed in view to establish the advantage of probing the two orthogonal linear hyperspectral polarization components for improving the passive remote detection and identification of liquid contaminants.

8873-17, Session 5

Thermally stable imaging channeled spectropolarimetry

Julia M. Craven-Jones, Brandyn M. Way, Jeffery P. Hunt, Sandia National Labs. (United States); Michael W. Kudenov, North Carolina State Univ. (United States); Jeffrey A. Mercier, Sandia National Labs. (United States)

Channeled spectropolarimetry can measure the complete state of polarization of light as a function of wavelength. Typically, a channeled spectropolarimeter uses high order retarders made of uniaxial crystal to amplitude modulate the measured spectrum with the spectrally-dependent Stokes polarization information. A primary limitation of conventional channeled spectropolarimeters is related to the thermal variability of the retarders. Thermal variation often forces frequent system recalibration, particularly for field deployed systems. However, implementing thermally stable retarders results in an athermal channeled spectropolarimeter that relieves the need for frequent recalibration. Recent work has identified two methods for producing thermally stable retarders for channeled spectropolarimetry. One technique combines multiple uniaxial crystals, while the other uses a biaxial crystal cut at a thermally insensitive angle. In this paper, we compare these two techniques in the context of producing an imaging thermally stable channeled spectropolarimeter. A preliminary design for a snapshot imaging channeled spectropolarimeter is also presented.

8873-18, Session 5

A novel design for a spectropolarimeter

Ad L. Verlaan, TNO (Netherlands); Hedser van Brug, TNO Science and Industry (Netherlands); Huib Visser, Technisch Physische Dienst-TNO (Netherlands)

We present a novel design for an Earth orbiting of high altitude spectropolarimeter for the measurement of aerosol concentrations. Purpose of the instrument is to measure both the radiance and the polarization state (degree and angle of linear polarization). As the degree of linear polarization is extremely sensitive to the microphysical properties of atmospheric or surface particles, this instrument can yield valuable information of these particles in the Earth's atmosphere. In previous studies (SPEX) an instrument was realized, targeted for operation on a Mars orbiter. Various experiments confirmed the instruments functionality and assessed its accuracy. This new design aims at measurements of the Earth's atmosphere. Core aspects in the instrument design are the absence of moving parts, the use of proven technology and a flexible and modular design. As a result an instrument is designed, based on a push broom spectrometer with a 30degree field of view and a 2.5km

by 2km instantaneous ground pixel. Spectropolarimetric measurements are performed over a wavelength range from 375nm to 850nm with a predicted measurement accuracy of better than 10-3 on the Degree Of Linear polarization.

8873-19, Session 5

Fabrication and performance evaluation of pixelated nano-wire grid polarizer

Shengkui Gao, Raphael Njuguna, Viktor Gruev, Washington Univ. in St. Louis (United States)

Metal-based nano-wire grid polarizer (NWGP) is a grid of periodic and parallel metallic wires that transmits parallel polarized light and reflects cross polarized light. It is widely used in division of focal plane (DoFP) imaging sensors to capture polarization information of the imaged environment. NWGP has benefits of thin form factor, wide field of view, high durability under UV exposure and temperature, etc. Extensive research work has been conducted to explore performance of NWGP with large areas regarding to feature size, thickness, duty cycle, and material. However, less work has systematically explored the NWGP at the pixel level. Advancement in nano-technology has enabled the fabrication of high performance NWGP structures in small area. A typical fabrication technique creates desired NWGP onto a substrate using a combination of lithography and etching techniques. In this work, we use electron beam lithography (EBL) and reactive ion etching (RIE) to fabricate aluminum pixelated NWGP structures. We present the procedure of the nano-fabrication, and evaluate the on-chip performance of the NWGP structures in terms of different orientations (0o, 45o, 90o, 135o), feature sizes (50nm to 500 nm), thicknesses (100nm to 200nm), and spectral response (450nm to 800nm). Based on the fabrication results and theoretical analysis, a pixelated NWGP model is developed and will act as a reference for future DoFP polarization imaging sensor design.

8873-20, Session 5

Wide field snapshot imaging polarimeter using modified Savart plates

Naooki Saito, Satoru Odate, Katsura Otaki, Nikon Corp. (Japan); Masahiro Kubota, Rintaro Kitahara, Kazuhiko Oka, Hokkaido Univ. (Japan)

We propose a snapshot imaging polarimeter using modified Savart plates for a wide field-of-view, and report a measurement error compensation. The snapshot imaging polarimeter using Savart plates consists of all passive optical components with the Savart plates, imaging lenses, wave plates, and a polarization analyzer. Spatial distributions of all four Stokes parameters can be determined simultaneously from a single image by using polarization interference patterns modulated at spatial carrier frequencies in the snapshot imaging polarimeter. Compared with conventional polarimeters which repeat several measurements of the light intensity distributions, our polarimeter has the capability of stable and fast Stokes measurements because of features of its configuration with no moving mechanical parts and no electrical components. Such feature is adequate to a real time measurement of spatial distribution of polarized light in a remote sensing application. For the purpose of a wide field-of-view with the feature effectively, we modified and improved the snapshot imaging polarimeter. The results from functional experiments show that there exist some measurement errors to be corrected and some optical components to be replaced for a wide field of view. To reduce those errors, we employed modified Savart plates and some calibration procedures of our polarimeter configuration. The verification experiments were carried out for the snapshot imaging polarimeter of the wide field-of-view.

8873-21, Session 5

An adaptive multi-channel spectropolarimeter(MSP) for identifying the spots of pollutants on the water surface

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The problem of detection and identification of the pollution spots on the water surface, especially of oil spills, is being solved by many scientists. The recently developed technology of an adaptive identification of the environmental elements from measurements in the visible spectral region permits to synthesize an expert system for an adaptive identification of the environmental parameters (ESAIEP). The system's structure includes a compact multi-channel spectropolarimeter (MSP), information interface with computer (IIC), computer software (STW), and extending database (EDB). The STW realizes a number of algorithms to process the data fluxes from MSP and provides service functions of visualization and control of the regime of measurements. The EDB consists of the sets of standard spectral images of the spots of pollutants represented by points in the multi-dimensional vector space of indicators, pre-calculated on the basis of learning samples.

The principle of the ESAIEP functioning is based on fixation of changes of the light flux at the MSP output and their transformation into a digital code. Further processing of these data with respect to their efficiency is determined by the STW composition containing various algorithms of recognition of 2D objects. The adaptability of the recognition procedure is determined by the level of accumulated knowledge about special features of intensity fluctuations and polarizing properties of the light reflected from the water surface. The STW includes the means that make it possible, in case of uncertain identification of the pollution spot, to make an expert decision based on the visual analysis of its spectral image. This procedure is realized in the mode of dialogue with ESAIEP, and if decision is made, the operator can fix it in the database in the form of a standard for subsequent situations of an appearance of similar spots.

8873-22, Session 5

SWIR active polarization imaging

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Nighttime active SWIR imaging has resolution and SWaP advantages over passive MWIR and LWIR imagers for applications involving target identification. We propose that the target discrimination capability of active SWIR systems can be extended further by exerting polarization control over the illumination source and imager, i.e. active polarization imaging. In this paper, we show how partial Mueller matrix signatures can be used to uniquely identify targets. This paper includes a description of the camera and laser systems used to collect these data; data reduction and analysis techniques; and an overview of a new method for Mueller matrix imager calibration.

8873-23, Session 6

Evaluation of Mueller matrix of achromatic axially symmetric waveplate

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In recent years, an axially symmetric polarized beam has been attracted attention in optical fields, because it has unique properties of states of polarization. There is a singularity of zero intensity at the center of the intensity distribution. For example a radial polarized beam is well-known as one of the axially symmetric polarized beam. This beam focused by an objective lens can generate z-polarization. Using these optical properties, the beam is used to optical tweezers, acceleration of electrons, super-resolution microscopes and so on. To generate the axially symmetric polarized beam, photonic crystals, liquid crystals, and sub-wavelength structure elements have been used. However, these elements strongly depend on both temperature and wavelength. From this background, we have proposed achromatic axially symmetric wave plates (AAS-WPs) with no spatial dispersion. The AAS-WPs has a concave conical surface similar to an element rotated about optical axis by the Fresnel rhomb. After a linearly polarized beam is incident on the AAS-WPs, Fresnel reflections are generated the phase difference. According to this, the total of phase differences is given by 90 degrees, achromatically. We designed a slope angle of the element based on Fresnel reflections. As a result, the slope angle was 44.3 degrees. The AAS-WPs has been made by SiO_2 to work coaxially. We evaluated the element by two-dimensional distribution of Mueller matrix. Moreover, we discussed the polarization properties of the AAS-WPs.

8873-24, Session 6

Compact spatial heterodyne interferometer using polarization gratings

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The implementation of an all polarization spatial heterodyne interferometer (SHI) is detailed. While a conventional SHI incorporates a Michelson interferometer and Littrow-configured diffraction gratings, the described polarization SHI exploits mechanically robust Wollaston prisms and polarization gratings. To this end, a theoretical model for the polarization SHI is developed and validated with data from proof of concept experiments. Additional modeling of the device is also incorporated to describe the PG's Mueller matrix in order to characterize non-ideal effects in the system. This included imaging the PG's Mueller matrix using a dual-rotating retarder Mueller matrix polarimeter. Comparisons to theory are made and error sources for the spatial heterodyning capability are described. Applications for this sensor includes high resolution spectroscopy in biomedical imaging, remote sensing, and machine vision.

8873-25, Session 6

Spectroscopic full polarimeters using spatial carriers

Kazuhiko Oka, Yujin Haga, Yoshihiko Komaki, Hokkaido Univ. (Japan)

The spectropolarimetry using spatial carriers are an alternative method for the snapshot spectroscopic measurement of the state of polarization (SOP) of light. In this presentation, we report on two implementations of the spectroscopic full-polarimetry using the spatial carriers. In the first implementation, a beam of light to be measured its spectroscopic SOP successively passes though a focusing lens, two Savart plates, an analyzer, and a Fourier transform lens. The entrance slit of a spectrometer with a two-dimensional CCD is placed on the back focal plane of the Fourier transform lens so that the spatial distribution of the spectrum along the slit can be resolved. The spatial intensity distribution at each wavelength includes three sinusoidal components carrying the information of the SOP. The frequency filtering along the spatial coordinate axis allows us to demodulate the four Stokes parameters at each wavelength. Accordingly, the wavelength-resolved Stokes parameters of the light under interest can be determined from a single two-dimensional spectrum. Unlike the channeled spectropolarimetry, the spectral resolution of the SOP measurement can be enhanced up to that of the spectrometer. In the second implementation, two achromatic birefringent prism pairs are used to generate a two-dimensional spectrum with spatial carriers. This implementation has an additional feature that the spatial carrier frequencies are less dependent on the wavelength variation. The feature allows us to decrease the limitation in the design of the spectropolarimeter. The feasibility of both implementations has been demonstrated by experiments in the spectral range between 450 and 800 nm.

8873-26, Session 6

Design of a polarimeter with two ferroelectric liquid crystal panels

Alba Peinado, Angel Lizana, Juan Campos, Univ. Autònoma de Barcelona (Spain)

Polarimeters are the basic instruments to measure the polarization of an electrical field and to determine the polarimetric interaction of that field with the matter. Nowadays, polarization metrology is used in many fields, such as in medicine, material characterization, remote sensing or astronomy.

Typical architectures of polarimeters are a rotating quarter wave plate and a polarizer, a set of polarization detectors arms initially divided by a beam splitter or a camera divided by macropixels based on a set of polarization analyzers.

Our work presents a polarimeter based on liquid crystal panels. This type of polarimeters presents an important advantage with respect to polarimeters based on mechanical elements because it is possible to avoid positioning misalignment errors by carrying out an accurate calibration before starting measuring, and so the initial elements offsets will be considered.

The polarimeter design is based on two ferroelectric liquid crystal monopixel panels, presenting a very fast polarization switching capability. It can be approximated as uniaxial birefringent waveplate layer with two stable optical axis orientations when a square electrical signal is addressed. Therefore, it can be modeled as a waveplate with a constant retardance, and with two possible orientations for its fast axis.

We have calibrated some important optical features of our ferroelectric panels: retardance, initial orientation and rotation of the optical axis. In addition, we have conducted an optimization of the orientation of these panels in the setup in order to obtain a minimum condition number of our polarimetric measurement matrix. Then, an experimental calibration is carried out and several measurements are taken in order to analyze its performance.

8873-28, Session 7

Identifying scattering functions from polarization correlations in backscattering

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Random electromagnetic fields (REF) have a number of distinctive statistical properties that may depend on their origin. There are situations when one can observe only the superposition of multiple underlying REFs caused by the interaction with different media. We show here that when two mutually coherent fields overlap, the individual characteristics are not completely lost. If prior knowledge about one of the fields is available, some information about the other one can still be retrieved. In particular, we will demonstrate that if assumptions can be made regarding the field correlation length of one of the overlapping REFs, the relative field correlation length of the second REF can be retrieved using the polarization properties of the combined field. High order field correlations such as the complex degree of mutual polarization (CDMP) provide the means.

We demonstrate experimentally that different effective scatter sizes can be identified even for depolarizing media which have, in average, the same diffusive properties. We examine the practically relevant geometry of backscattering and find that that the single scattering contribution largely retains the information about the state of polarization of the incident field. Examining the spatial extent of the CDMP correlation provides a straight measure of the spatial coherence properties of the REF primarily caused by single scattering, which is directly related to particle size and its scattering properties. It should be emphasized again that all the information recovered is the result of a single realization of the random interaction between light and matter.

8873-29, Session 7

The retrieval of scattering coefficient of marine particles from polarimetric observations

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Polarized light in the oceans carries intrinsic information that can be utilized to estimate the optical and microphysical properties of the oceanic hydrosols. It is especially sensitive to the scattering coefficient, which cannot be retrieved from the unpolarized light used in current ocean color remote sensing algorithms. Through the unpolarized remote sensing reflectance (Rrs), these classical algorithms can only estimate backscattering coefficients bb, but the total scattering coefficient b could be solely retrieved based on the characteristics of polarized light. The correlation is quantified in this paper. Based on extensive simulations using the vector radiative transfer program RayXP, the attenuation-to-absorption ratio (c/a), from which b is readily computed, is shown to be closely related to the degree of linear polarization (DoLP). The relationship is investigated for the upwelling polarized light for several wavelengths in the visible part of the spectrum, for a complete set of viewing geometries, and for varying concentrations of phytoplankton, non-algal particles, and color dissolved organic matter (CDOM) in the aquatic environment. It is shown that there is an excellent correlation between the DoLP and c/a for a wide range of viewing geometries. That correlation is investigated theoretically using fitting techniques, which show that it depends not only on the general composition of water but also on the particle size distribution (PSD) of the (mainly non-algal) particles. A large dataset of Stokes components for various water compositions, measured in the field with a hyper-spectral and multi-angular polarimeter, then provides the opportunity to validate the parameterized relationship between DoLP and c/a. This study opens the possibility for the retrieval of additional inherent optical properties (IOPs) from air- or space-borne DoLP measurements of the ocean.

8873-30, Session 8

Fully polarimetric passive W-band millimeter wave imager for wide area search

Jonathan R. Tedeschi, Bruce E. Bernacki, James F. Kelly, David M. Sheen, Douglas L. McMakin, Thomas E. Hall, Brian K. Hatchell, Patrick L. J. Valdez, Pacific Northwest National Lab. (United States)

We describe the design and phenomenology imaging results of a fully polarimetric W-band millimeter wave (MMW) radiometer developed by Pacific Northwest National Laboratory for wide area search. Operating from 92-94GHz, the W-band radiometer employs a Dicke switching heterodyne design isolating the horizontal and vertical MMW components with 40dB of polarization isolation. Design results are presented for both infinite conjugate off-axis parabolic and finite conjugate off-axis elliptical fore-optics using optical ray tracing and diffraction calculations. The received linear polarizations are down converted to a microwave frequency band and recombined in a phase shifting network to produce all 6 orthogonal polarization states of light simultaneously, which are used to calculate the Stokes parameters for display and analysis. The resulting system performance produces a heterodyne receiver noise equivalent delta temperature (NEDT) of less than 150mKelvin. The radiometer provides novel imaging capability by producing all four of the Stokes parameters of light, which are used to create imagery based upon the polarization states associated with unique scattering geometries and their interaction with the downwelling MMW energy. The polarization states can be exploited in such a way that man-made objects can be located and highlighted in a cluttered scene using methods such as image comparison, color encoding of Stokes parameters, multivariate image analysis, and image fusion with visible and infrared imagery. We also present initial results using a differential imaging approach use to highlight polarization features and reduce common mode noise. Persistent monitoring of a scene using the polarimetric passive mm-wave technique shows great promise for anomaly detection caused by human activity.

8873-31, Session 8

Simulations of polarization dependent contrast during the diurnal heating cycle for passive millimeter-wave imagery *(Invited Paper)*

John P. Wilson, Maciej Murakowski, Univ. of Delaware (United States); Christopher A. Schuetz, Phase Sensitive Innovations, Inc. (United States); Dennis W. Prather, Univ. of Delaware (United States)

Passive millimeter-wave (mmW) sensors operate in a unique part of the electromagnetic spectrum that is able to penetrate through a variety of common obscurants while still producing resolutions that are adequate for human operators to identify targets of interest. Their passive nature can be important for military applications and they are especially suited to persistent surveillance applications due to their ability to operate independently of day/night conditions and through transient atmospheric obscurants such as clouds, rain and fog.

The radiometric temperature of objects will change throughout the day since the radiometric temperature is dependent on the kinetic temperature. As the kinetic temperatures of different objects change at different rates, the contrast between objects will vary throughout the day (the same is true for infrared imagery). Since mmW imagery is heavily dependent on the reflections of objects and not just the kinetic temperature, imagery is often strongly polarized. This is especially relevant for passive mmW sensors since many of these sensors are only able to detect a single linear polarization state (often due to waveguide and component limitations).

Simulations are presented from a modified open source ray-tracing program called Blender. The new program incorporates a sky temperature generator as well as the ability to modify the dielectric constants and kinetic temperatures of different objects. The ability to measure different linear polarization states has also been added, allowing for polarimetric modeling capability. Simulations show large differences of contrast between different polarization states of radiation throughout the day. In extreme cases, the contrast of a target can drop to zero during a crossover event for a linear polarization state while the orthogonal polarization state exhibits contrasts on the order of 10 K. Preliminary experimental results are also presented from a passive mmW polarimetric sensor during a 24 hour test.

8873-32, Session 9

Polarization display based on the human visual system just noticeable difference

Adoum H. Mahamat, J. Scott Tyo, College of Optical Sciences, The Univ. of Arizona (United States)

Polarization imaging infers the orientation of the electric field of light that is coming from the illuminated objects in the scene being imaged. Our group and several other groups have been working on the measurement of the optical polarization information on natural scenes. Even though mathematical analyses allow us to know the orientation of the electric field, the human vision system is not able to perceive polarization, and human observers generally have no experience interpreting polarization data. A number of methods have been developed to represent polarization data in pseudocolor, texture, and motion. However, no studies have been performed to our knowledge that test the usefulness of any of these methods to assist observers in performing tasks. In this study we are designing several visual tasks for observer to accomplish while looking at polarization information displayed using various representation methods. We design the study using several tasks that include finding an object in scenes, and tracking a target in the presence of clutter. In this task two methods of polarization display are presented. First method uses colorfuse based on a hue equation that we determined using the human visual system (HVS) response to the just noticeable difference (JND) in color as well as a method using coherent motion of dots. In the coherent motion of the dots, polarization is displayed with dots moving in the direction of orientation of the E-field, and dot sizes or randomness determine degree of polarization. Collected data will be compared as a result.

8873-35, Session 9

Material characterization using passive multispectral polarimetric imagery

Melissa Sawyer, Air Force Institute of Technology (United States)

A new method for characterization of unknown targets using passive multispectral polarimetric imagery is presented. Previous work makes use of a pBRDF derived equation for the degree of linear polarization and with the aid of multiple incidence angles estimates refractive index and reflection angle. This work uses known incidence and reflection angles along with dispersion equations and polarimetric data at multiple wavelengths to recover the index of refraction. Although imagery is collected with a division of amplitude polarimeter in iterative, manual steps, this algorithm could be applied to the data produced by a recently introduced compact division of focal plane multispectral polarimeter with many remote sensing applications. Experimental results are presented showing the new method's ability to characterize a range of materials.

8874-1, Session 1

Deep turbulence propagation of a Gaussian-beam wave in anisotropic non-Kolmogorov turbulence *(Invited Paper)*

Larry C. Andrews, Ronald L. Phillips, Robert Crabbs, Univ. of Central Florida (United States); Troy T. Leclerc, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

In the conventional Kolmogorov model of turbulence the turbulent fluctuations of the index of refraction are assumed to be statistically homogeneous and isotropic, and there is a specific mathematical form for the power spectral density of the index of refraction fluctuations. Development of the turbulent theory of passive scalar transfer has shown that although the conventional Kolmogorov spectrum model with a 11/3 power-law index is generally correct near the ground (within the inertial subrange), it constitutes only one part of the more general behavior of passive scalar transfer in a turbulent flow. Hence, deviations from the conventional Kolmogorov model are possible. In this study we develop theoretical models for beam spot size, beam wander, spatial coherence, and scintillation index that are valid in weak irradiance fluctuation regimes as well as in deep turbulence or strong irradiance fluctuation regimes. These theoretical models are based on power-law index variations from 11/3 in the spatial power spectrum model of atmospheric turbulence in addition to anisotropic conditions.

8874-2, Session 1

Comparison of the split-step method for various power spectral models

Heba Yuksel, Demet Yuksel, Bogaziçi Üniv. (Turkey)

Turbulence remains an important unsolved problem of classical physics. When the collimated beams traverse the striated region, the beam first suffers random phase perturbations due to variations in the phase velocity within the medium. These phase variations in the propagating wavefront introduce small random changes in the direction of propagation of the beam. Thus portions of the once plane wavefront now propagate in different directions relative to other portions. As the beam propagates further, diffraction or angular scattering causes constructive and destructive interference which introduces fluctuations in amplitude as well as phase. These time-varying amplitude and phase fluctuations represent an undesired complex modulation of the carrier. We propose a phase-screen method based on a split-step approach to numerically solve the parabolic wave equation. The accuracy of the split-step solution for wave propagation in random media is proven by variety of studies but it will be the first in its field that the aperture averaging factor will be explored using the split-step method. In our previous work, the Modified Kolmogorov spectrum has been used in the modeling. In this work, different spectral models will be used and the effect of the model on the results will be investigated. All of our simulation results will be compared with other simulation models as well as empirical results. Our simulation will be unique and useful in developing a better turbulence model within all of the turbulence regimes.

8874-3, Session 1

Optical signal fade-time statistics for multiple-aperture communications in atmospheric turbulence

Troy T. Leclerc, Univ. of Central Florida (United States)

Mean and variance of optical signal fade-time for multiple aperture communication system in atmospheric turbulence are analyzed. Closed form expressions are presented and compared to experimental results obtained by an array of receiving apertures located at the Townes Institute Science and Technology Experimentation Facility (TISTEF) 1km laser range located within the Kennedy Space Center at Cape Canaveral, FL. Measurements are made under various turbulence conditions, ranging from weak to strong, over multiple days of operation. Simultaneous measurement of weather conditions and scintillometer instrumentation are utilized to verify atmospheric conditions. Signal quality of multiple apertures is compared to the signal quality of a single aperture receiver. The fade-time statistics of apertures of identical size diameter, and non-identical size diameter, are compared. Spacing distance between apertures and improvement related to the total number of apertures is considered. Gamma-gamma irradiance model is utilized to obtain theoretical results; the gamma-gamma model has previously been shown to be an effective prediction for both the weak and the strong fluctuation regime.

8874-4, Session 1

Wave optics simulation for beams with spatially varying coherence properties

Xifeng Xiao, David G. Voelz, New Mexico State Univ. (United States)

Propagation studies of partially coherent beams typically assume a Gaussian Schell model where the spectral degree of coherence between two spatial points is assumed to be spatially stationary. Partially coherent beams with spatially varying coherence functions have been recently introduced and it is believed that the design flexibility of this type of beam can lead to improved performance for applications such as free space laser comm. Some theoretically analysis exists for certain spatially varying coherence classes, however, verifying the results and extending the analysis to more cases is difficult due to the complexity of the problem. In this work we propose a numerical wave optics approach for simulating the propagation of a beam with spatially varying coherence properties. The concept involves the development of a random screen with the spatially varying correlation properties that is implemented in the source plane. A large sequence of screen realizations is applied and the intensity results after propagation are averaged to yield the partially coherent result. This approach allows the propagation characteristics of a wide range of beam types to be evaluated. In this paper we describe the method and present several propagation examples of "designer" beams with spatially varying coherence.

8874-5, Session 1

Measurement system for analysing the spectral radiation pattern of light sources for FSO systems

Pimrin Pezzei, Erich Leitgeb, Nacira Stiebler, Markus Loeschnigg, Technische Univ. Graz (Austria)

For the verification of Free Space Optics systems it is common to determine optical power measured depending on illuminated area at a certain wavelength. In the context of this work a new measurement system was developed, which is able to measure not only the optical power but also the complete spectral distribution of the light beam. Free Space Optics (FSO) is becoming more and more important, because of the high usable bandwidth (leading to high data-rates) in optics compared to RF.

The paper is structured into 5 main parts. After a short introduction the authors show the theoretical background of the relevant optical beam

distributions, the mechanical and electrical set-up of the measurement, before the graphs and figures illustrate the measurement results.

The measurement system consists of a mechanical structure, where a collimator is mounted on. This collimator can be moved in two dimensions to enable the measurement of predefined points. It is connected with a spectrum analyzer using an optical fibre. A PC controls the position of the collimator and initiates the spectrum analyzer to record the spectral curves, the maximum peak of power, the -3dB bandwidth and the total power of spectrum. The obtained data covers a measurement area of 0.91 m by 0.77 m which can be surveyed at a high local resolution of 0.7 mm. Collimated beams in the range between 600 and 1750 nm are analysed.

8874-40, Session 1

Statistical characterization of fluctuations of a laser beam transmitted through a random air-water interface: new results from a laboratory experiment *(Invited Paper)*

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No Abstract Available

8874-6, Session 2

Retrieval of structure functions of air temperature and refractive index from large eddy simulations of the atmospheric boundary layer

Jeremy A. Gibbs, Chris Wilson, Evgeni Fedorovich, The Univ. of Oklahoma (United States); Alexander M. J. van Eijk, TNO Defence, Security and Safety (Netherlands)

Structure functions and associated structure-function parameters of meteorological variables are extensively employed in practical applications for quantification of the spatial variability of atmospheric turbulent flow fields. Particularly, turbulent fluctuations of temperature and humidity can strongly affect the propagation of acoustic and electromagnetic waves in the atmosphere by causing the variability of the refractive properties of the air. Such fluctuations can also significantly modify the transmission of signals from remote sensing devices, such as radars and sodars, which are increasingly popular tools for investigation of the atmospheric structure.

In this study, the second-order structure functions of air temperature and refractive index are directly evaluated from numerical large eddy simulation (LES) output for representative atmospheric boundary-layer flow cases. Since LES provides values of the considered flow variables at the very high spatial (of the order of few meters) and temporal (of the order of seconds) resolution in a domain that extends throughout the entire boundary layer and even above it, it appears promising to use LES output data for practically-oriented structure-function parameter calculations. In previous attempts to evaluate structure-function parameters from LES data, they were typically estimated through supplementary relations between these parameters and turbulence dissipation rates.

Calculated structure functions of temperature and refractive index in many cases exhibited 2/3 power slopes over extended ranges of separation distances. The structure-function parameters were evaluated within these scale ranges. Lower limits of the 2/3 slope range depended on the spatial resolution and subfilter-scale closure employed in LES. The behavior of structure-function parameters evaluated from LES in the lower portion of the CBL generally agreed with predictions by Monin-Obukhov similarity relationships that are commonly employed for evaluation of the structure-function parameter in the atmospheric surface layer. Under convective conditions, the non-dimensionalized structure-function parameter for humidity was strongly influenced by entrainment at the boundary-layer top. Spatial anisotropy of turbulence structure in the boundary layer was investigated through comparison of structure functions calculated along individual horizontal coordinate directions.

8874-7, Session 2

GPS synchronized UV communication system performance based on USRP

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Recently, Ultraviolet communication is paid more and more attention, with its solar blind and Non-Line-of-Sight characteristic. However, it is hard to capture and recover the transmitted signal outdoor without synchronized signal. In this work, we integrate GPS clock into Universal Software Radio Peripheral (USRP) based UV communication system and employ it as synchronized signal. At receive side, photon counting and adaptive threshold method are used to recover original signal. Through experiments, we test the BER of the UV system under different configuration geometry. Some results compared to the normal UV system without synchronized signal are also presented.

8874-8, Session 2

Scattering and propagation of UV pulses in soot aerosols

Haiying Li, Zhensen Wu, Lu Bai, Yunhua Cao, Yanhui Li, Xidian Univ. (China)

As the rapid development of UV band research, the applications of UV wave in communication, imaging, detective and other fields attract more and more attention. Multiscattering of complicated environments may cause amplitude fluctuation, pulse broading[1].

Generally, soot aerosols can be seen as the random aggregate systems, which are composed of the unburned fuel and dust. Compared with the wavelength of UV band, aggregate systems can be considered as the cluster of spherical elements. Generally, these soot aggregate systems have complex structure and fractal properties. The propagation of UV pulses in random aggregate systems plays an important role in the UV communication field.

Several electromagnetic scattering theories have been published regarding multi-sphere scattering [2–4], Such as, the discrete-dipole approximation(DDA) [2], Generalized Lorenz-Mie theory[3], and the generalized multi-particle Mie-Solution(GMM) [4]. These methods are widely applied to an arbitrary aggregate of spherical particles.

A number of important studies have been reported on the propagation of plane wave and beam wave pulses in random media by many investigators[5-9]. Ishimaru[5] developed the theory of pulse propagation in discrete random media, derived the correlation function of a wave in a random distribution of stationary and moving scatters, and reported the multiple scattering effects on coherent bandwidth and pulse distortion of a wave propagating in a random distribution of particles.

In this paper, Scattering and propagation of UV pulses in random soot aggregate system are studied using generalized Multi-sphere Mie theory(GMM) and pulse wave propagation theory. Soot aggregates are obtained by the DLA model. For soot aggregate, scattering characteristics of a single aggregate in soot aggregate systems are analyzed by GMM. Scattering intensities versus scattering angles are given. The effects of different-positions average of the aggregate on the scattering intensities, scattering efficiency factors, extinction efficiency factors and absorption efficiency factors are computed and compared. The results obtained from GMM will provide some parameters for the analysis of propagation of pulses in random soot aerosols.

Based on pulse wave propagation in random media presented by Ishimaru[5], the transmission of UV pulses in random soot aggregate system is determined by the two-frequency mutual coherence function.

Numerical simulations of two-frequency mutual coherence function, coherent bandwidth are given and analyzed for UV pulses. The effects of soot aerosols parameters are discussed.

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8874-9, Session 3

Innovative beacon approach for turbulent atmosphere characterization *(Invited Paper)*

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Characterization of atmospheric perturbations is critical for effective compensation of turbulence-induced effects in coherent and incoherent imaging, laser communication and laser beam propagation, in general. The related parameters of the turbulence are derived by detecting the characteristics of a reference wave passing through an inhomogeneous medium. On practice, this requires a reference wave generated by a localized beacon placed at the opposite end of the light path where the parameters of the turbulence will be measured. Therefore, the beacon is critical for various systems that perform characterization of perturbations and its correction systems, including the adaptive optics. Formation of the beacon in a turbulent environment remains one of the most pressing and difficult-to-solve problems, especially in the case of an extended or image-resolved target with a diffuse-scattering surface.

To date, several approaches targeting the formation of a localized beacon have been attempted with little success. Most of the proposed methods and techniques have been simulated and studied experimentally in laboratories, but didn't prove a reliable performance in a realistic environment, mostly due to the complexity of the problem. The most effective solution to the problem would be to develop a system for atmosphere characterization that can use the light scattered by a non-localized extended target. This presentation discusses the results of the analysis, simulations and experimental studies of the technique that allows characterization of turbulence in an image-resolved scenario.

8874-10, Session 3

Pointing, acquisition, and tracking considerations for mobile directional wireless communications systems

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High capacity directional wireless communications networks are an active research area because of their Gb/s or greater data-rates over link lengths of many kilometers, providing fiber-like networks through the air. Their high data-rates arise partly from their very high carrier frequencies and partly because of their narrow beamwidths. This second characteristic requires that transceivers be pointed precisely to their counterparts. In almost all cases this means that the transceiver aperture is mechanically pointed by a rotation stage, commonly known as a gimbal. How these platforms initially point at a target, acquire the signal, and then stay locked on the signal is known as pointing, acquisition, and tracking (PAT). Approaches for PAT in both RF and FSO have some similarities, but require overall divergent solutions, especially if the platforms are moving. This paper elaborates on the various considerations required for designing and implementing a successful PAT system for both directional RF and FSO systems. In particular, approaches for GPS or beacon based pointing, types of acquisition scans, totally blind acquisition possibilities, and different tracking algorithms are analyzed. Finally, some results from a custom built six platform FSO system are described, along with their use as a testbed for future PAT experiments.

8874-11, Session 3

An innovative modulating retro-reflector for free-space optical communication

Etai Rosenkrantz, Shlomi Arnon, Ben-Gurion Univ. of the Negev (Israel)

Modulating retro-reflectors (MRR) are beneficial for asymmetric free-space optics communication links. An MRR includes an optical retro-reflector and an electro-optic shutter. The main advantage of an MRR configuration is that it shifts most of the power, weight, and pointing requirements onto one end of the link. In this study an innovative device comprising of nanoparticle-embedded ferroelectric thin film is used as an MRR. The new modulator is mounted in front of a passive retro-reflector. In our study we calculated the link budget for lunar exploration scenario. The scenario includes a base station that communicates with several robots or astronauts. In our simulations, the base station illuminates a robot with a continuous-wave beam, i.e. an interrogating beam. The un-modulated beam strikes the MRR, which is located on the robot, and is passively reflected back to the base station carrying the data that has been modulated onto it by the MMR. In this scenario a robot and a base-station are 4km apart, with a clear line of sight. In addition, the innovative MRR is capable of achieving 12dB contrast ratio. Under these assumptions and using the nanoparticle-embedded ferroelectric MRR we calculated the required transmission power for a given bit-rate and BER.

8874-12, Session 3

Comparison and evaluation of the laser beam-shaping techniques

Peter Barcík, Lucie Hudcová, Otakar Wilfert, Brno Univ. of Technology (Czech Republic)

Over the past several decades, free-space optical (FSO) systems have gained a specific place in the wireless technology area. The application of these systems is advantageous for high bandwidth, a license free band and quick installation. The main drawback of FSO systems is their dependence on the state of the atmosphere causing deterioration of the

FSO systems availability. One of the atmospheric effects which has an essential impact on the performance of the FSO systems is atmospheric turbulence. Atmospheric turbulence leads to fluctuation of the optical intensity in the plane of the receiving aperture. It has been shown that to reduce the effect of atmospheric turbulence, uniform distribution of the optical intensity within a cross section of the beam in the plane of transmitting aperture (phenomenon of diffraction is neglected) and a sufficiently large diameter of the circularly symmetric receiving aperture (to achieve aperture averaging effect) are needed. The main idea of our paper is the problem of beam shaping at the transmitter. In our contribution the technique of transformation of a Gaussian beam into a beam with uniform distribution of optical intensity is discussed. For the mentioned transformation we experimentally tested several shaping methods such as multi aperture beam integrators, diffractive diffusers, etc. Usage of laser sources with different degrees of coherence was considered.

The purpose of these techniques is to create an optical beam with uniform distribution of optical intensity on the transmitter output. In order to compare and evaluate the particular shaping techniques, a new "Transformation Complex Quality (TCQ) parameter" was defined. The TCQ parameter indicates the optimal shaping technique and also evaluates the quality of the resulting transformed beam with respect to its resistance towards atmospheric turbulence.

8874-13, Session 3

Extracting atmospheric turbulence and aerosol characteristics from passive imagery

Colin N. Reinhardt, David Wayne, Kevin McBryde, Galen Cauble, SPAWAR Systems Ctr. (United States)

Obtaining accurate and timely information about local atmospheric meteorological conditions such as turbulence and aerosol/particulate content remains a difficult problem with incomplete solutions. It has important applications in optical and IR free-space communications, imaging systems performance, and the propagation of directed energy. The capability to utilize passive imaging data to extract parameters characterizing atmospheric turbulence and aerosol/particulate conditions would represent a valuable addition to the current toolset for atmospheric sensing.

Our research investigates the novel application of fundamental results from optical turbulence theory and aerosol extinction theory combined with current blind/no-reference image-quality-metrics (IQM) and image-quality-assessment (IQA) methods. We have developed an algorithm which extracts important parameters used for characterizing atmospheric turbulence and aerosols/particulates along the propagation channel, such as the refractive-index structure function C_n^2 , the Fried atmospheric coherence width r_0, and the atmospheric extinction coefficient ?, from passive image data of remote Siemens star resolution targets. We will analyze the algorithm performance using simulations based on modeling with turbulent and aerosol modulation transfer functions (MTF), and high-resolution wave-optics phase-screen propagation computational models. An experiment campaign was organized and data were collected from passive imaging of Siemens star resolution targets over a 700m littoral path in San Diego. We examine the algorithm's effectiveness using this data and compare against measurements taken concurrently with other standard atmospheric characterization equipment.

8874-14, Session 4

Propagation of light through ship exhaust plumes *(Invited Paper)*

Miranda van Iersel, TNO Defence, Security and Safety (Netherlands)

Looking through the atmosphere it is sometimes difficult to see the details of an object. Looking through exhaust plumes of e.g. a ship can make it even harder to see the details. Exhaust plumes come in different shapes, sizes, and opaqueness and they depend on atmospheric parameters like wind speed and direction, as well as engine settings (power, gas or diesel, etc.).

A model to characterize the plume as function of the aforementioned parameters has been developed and an analysis was made of amount of detail still visible through a plume under different conditions.

This plume module will be incorporated in the TNO EOSTAR-model, which provides estimates of detection range and image quality of EO-sensors under varying meteorological conditions. The plume module improves EOSTAR in two aspects, i.e., a more accurate calculation of a ship's signature and the shading of the scene behind the ship due to plume absorption.

8874-15, Session 4

A novel method for measuring atmospheric transmission using a modulated laser source

David Wayne, Colin Reinhardt, Kevin McBryde, Galen Cauble, SPAWAR Systems Ctr. (United States)

Current transmissometer designs can be physically bulky, electronically complex, and susceptible to background light; ultimately limiting performance. We describe a novel transmissometer design based upon a modulated laser/LED source and an AC-coupled receiver to improve upon the aforementioned shortcomings. This design aims to reduce both complexity and SWAP through the use of a high frequency modulation technique. We describe the theory associated with our technique, particularly how the effects of atmospheric turbulence are handled. The transmissometer is built and tested in the laboratory then demonstrated over a 700m littoral path in San Diego; an Optec PLV-3 commercial transmissometer is setup in parallel to provide a baseline atmospheric transmission measurement. Two signal processing techniques are described, one to calculate the atmospheric transmission and the other to calculate the optical depth. The processed data are compared with concurrent measurements from an Optec LPV-3 commercial transmissometer. The data from the new transmissometer tracks the commercial instrument very well.

8874-16, Session 4

Modified plenoptic camera for phase and amplitude wavefront sensing

Chensheng Wu, Christopher C. Davis, Univ. of Maryland, College Park (United States)

A plenoptic camera is a camera that preserves the light field entering its object lens and facilitates future processes such as refocusing at different depths and 3D microscopy. It is also changing the paradigm in photography, allowing people to take casual shots first but produce high quality pictures later. This new generation of camera incorporates a micro-lens array where the image sensor of a traditional camera would be and places a focal plane array in the focal plane of the micro-lens array. This forms a tiny camera array recording each spot in the aperture of main objective lens. By acquiring extra information about a scene and weighted averaging of this data, the plenoptic camera provides additional information to traditional cameras. We have determined that with slight geometric changes of its components, a modified plenoptic camera will be able to solve phase and amplitude wave front sensing problems such as analyzing interference patterns and recording phase difference between light patches of a distorted laser beam. Our modified plenoptic camera uses the micro-lens array as a viewing tool aimed at the focal plane of the main objective lens. In combination with Fourier optic analysis, a complex wave-superposition is sorted and divided into much simpler wave forms on different regions of the final image plane, which can be recorded and analyzed. Simulations have been conducted to verify these concepts, and show that this modified plenoptic camera can reveal phase information in addition to spatial and angular information provided by a traditional Shack-Hartmann Wave front sensor. This may lead to promising approaches for correcting atmospheric turbulence induced distortions on laser beams that have passed through deep turbulence.

8874-17, Session 4

Multifractality and the effect of turbulence on the chaotic dynamics of a HeNe laser

Damián Gulich, Luciano Zunino, Ctr. de Investigaciones en Óptica, A.C. (Argentina) and Univ. Nacional de La Plata (Argentina); Darío Pérez, Pontificia Univ. Católica de Valparaíso (Chile); Mario Garavaglia, Ctr. de Investigaciones en Óptica, A.C. (Argentina) and Univ. Nacional de La Plata (Argentina)

We propose the use of multifractal detrended fluctuation analysis (MF-DFA) to measure the influence of atmospheric turbulence on the chaotic dynamics of a HeNe laser. Fit ranges for MFDFA are obtained with goodness of linear fit (GoLF) criterion.

The chaotic behavior is generated by means of a simple interferometric setup with a feedback to the cavity of the gas laser. Such dynamics have been studied in the past and modeled as a function of the feedback level. Different intensities of isotropic turbulence have been generated with a turbulator device, allowing a structure constant for the index of refraction of air adjustable by means of a temperature difference parameter in the unit.

Considering the recent interest in message encryption with this kind of setups, the study of atmospheric turbulence effects plays a key role in the field of secure laser communication through the atmosphere. In principle, different intensities of turbulence may be interpreted as different levels of white noise on the original chaotic series. These results can be of utility for performance optimization in chaotic free-space laser communication systems.

8874-22, Session PMon

Propagation and split of the filamentation of femtosecond pulses in air by multiphase screen method

Jifeng Zu, Qijie Huang, Xusheng Zhou, Peng Zou, Yameng Zheng, Ting Yu, Shanghai Institute of Optics and Fine Mechanics (China); Yimeng Wang, Yachen Gao, Heilongjiang Univ. (China)

The propagation and split of the filamentation of femtosecond pulses in air have been paid much attention since last a few years. However, most research works are performed with few considerations of the turbulence effects of atmosphere due to the difficulties of utilizing analytical solutions and experiment conditions. In this work, we will attempt to introduce a kind of numerical simulation method to analyze the transmission features of femtosecond laser pulses in air or in the turbulent air, namely, it is called multi-phase screen method (MPSM) which use phase screen to simulate atmospheric turbulence. In this presentation, the main laser parameters are as follows: 85 fs pulse-width, 0.8cm radius of the beam, the two kinds of 160GW and 1.0 TW peak-power operating at 800 nm. Then utilizing the structure of Vortex soliton to control the filamentation is proposed. In our cases, four Gaussian pulses with a difference of $\pi/2$ in the phase of each adjacent beam as a ring to control the filamentation by utilizing its characteristics of the vortex soliton. Some results show that the coupling and interaction among four Gaussian pulses cause the rotational transfer of the energy of the four beams. Finally, we obtain the transmission features of the beams propagating in the turbulent air with different intensities by the MPSM.

8874-35, Session PMon

Space qualified photon counting detector package

Josef Blazej, Ivan Prochazka, Czech Technical Univ. in Prague (Czech Republic); Jan Kodet, Czech Technical Univ. in Prague (Czech Republic) and Technische Univ. München (Germany)

The laser time transfer link is under construction for the European Space Agency for its application in the experiment Atomic Clock Ensemble in Space. We have developed and tested the photon counting detector optimized for operation in space for this project. The detector package is rugged and compact. The optical, photon counting, electrical and timing properties of the detector package have been tested. In this paper are reported the main characteristics which changed after the irradiation by ionizing radiation. The effective dark count rate was measured using actively quenching and gating circuit. It will be used also during space operation. The radiation sources was protons at 53 MeV and gamma ray radiation source 60Co. The long term detection delay stability in the sense of time deviation of detected single photon signal is excellent – typically 200 fs for averaging times of several hours. The device is capable to operate in a temperature range of ?55°C up to +60°C. The change of the detection delay with temperature is typically below 500 fs/K. The detector has been approved for application in the European Laser Timing experiment, the flight module is under manufacturing now. The detector might be employed in other future space missions including long-term, where sub-picosecond timing and radiation stability is required and interesting for other photon counting application under ionizing radiation.

8874-36, Session PMon

Prototyping FM data demodulation in free-space optical communication systems using discrete wavelet transformation

Lan Tran, Esam El-Araby, Nader M. Namazi, The Catholic Univ. of America (United States)

One of the inherent limitations on the quality of a free-space optical (FSO) communications link is the degradation of the received beam due to atmospheric turbulence. Some of the effects of atmospheric turbulence on FSO received beams are beam wander, beam break-up, and scintillation. All of these atmospheric effects can cause a reduction of signal to noise ratio (SNR), reduction in effective link range and/or bandwidth, and often complete loss of the received data. Atmospheric turbulence effects are especially difficult to overcome in the case of analog modulation of the optical beam since fluctuating received power levels translate directly to fluctuations in the amplitude of the modulating signal.

In this paper, we consider the effects of atmospheric turbulence on an FSO link that uses analog frequency modulation. The atmospheric effects are treated as noise signals which decrease the signal-to-noise ratio of the link. Based on the results presented in [1], we investigate the use of the discrete wavelet transformation (DWT) to considerably reduce the effect of the noise signals. The method in [1] will be used and implemented real-time on FPGA using Xilinx System Generator for DSP.

[1] Nader Namazi, Ray Burris, G. Charmaine Gilbreath, Michele Suite and Kenneth Grant, "Demodulation of FM Data in Free-Space Optical Communications Systems Using Discrete Wavelet Transformation", in Discrete Wavelet Transforms - A Compendium of New Approaches and Recent Applications, Awad Kh. Al – Asmari, Ed, New York: Intech, 2013.

8874-37, Session PMon

Phase-space distribution of optical field intensity of laser beam propagation through atmospheric turbulence

Wei Lu, Jianfeng Sun, Deyan Xu, Xiaoping Ma, Bing Li, Liren Liu, Shanghai Institute of Optics and Fine Mechanics (China)

Phase-space optics has its advantage over the research of laser beam propagating through atmospheric turbulence channel due to its special joint space-spatial frequency representation, which can be used to describe the property of optical signals between variables that form a Fourier transform pair. In this paper, we try to introduce the effect of atmospheric turbulence in terms of matrix into the phase-space analysis of laser beam propagation through turbulence. The far field optical intensity in the channel will be given in terms of phase-space representation and the phase-space distribution of received optical intensity can be plotted. Furthermore, we also try to deduce phase-space representation of several turbulent layers and get the combined result. We try to give the phase-space representation of optical scintillation if possible, which may be a new method analyzing optical scintillation under the turbulent condition.

8874-38, Session PMon

The effects of the relay beam size and data rate on self-homodyne detection efficiency in the satellite-to-ground laser communication

Xiaoping Ma, Jianfeng Sun, Ya'nan Zhi, Wei Lu, Liren Liu, Qian Xu, Shanghai Institute of Optics and Fine Mechanics (China)

Atmospheric turbulence influences the wave-front, and reduces homodyne detection efficiency and bit error rate in the Satellite-to-Ground Laser Communication. Free-space differential interference structure based on differential phase shift keying (DPSK) is applied in the optical signal receiver. The free-space Mach-Zehnder delay interferometer without lens is suited for differential delay which is equal to the one bit period. Differential information is obtained by the subtraction of the two successive wave-front phases when made to interfere. Differential distance at the interference receiver is varied with transmission rate from satellite to ground. And through the receiving telescope, the spot size of incident signal light within the interference became small than before, which influences the interference efficiency of the two unequal branches. So that, it is significant for increasing homodyne efficiency to determine the optical signal rate and choose the magnification of receiving telescope. In this paper, the effect of the spot size of incident light and transmission data rate on homodyne detection efficiency is analysed. By the simulation result of efficiency in different spot size and transmission date of incident light, the homodyne efficiency will be predicted in the given data rate and light spot size on the basis of experiment setup. And application condition of free-space differential structure at DPSK differential receiver is proposed.

8874-39, Session PMon

Measurement and modeling of the effects of atmospheric turbulence on coherent laser communication system

Jian Zhou, Wei Lu, Jianfeng Sun, Liren Liu, Shanghai Institute of Optics and Fine Mechanics (China)

It is well known that optical field propagates through the atmospheric channel is subject to random fluctuations in phase and amplitude which are caused by atmospheric turbulence. For the heterodyne reception free space coherent laser optical communication (FSO) system, phase fluctuation results in the mismatch between the signal field and the local oscillator. As a result, loss of heterodyne efficiency will occur. In recent years, much attention has been paid to adaptive optics and many techniques have been presented to correct the wave-front distortion. However, it is necessary to study how the effects of atmospheric turbulence on FSO system performance can be predicted and modeled. In this paper, we describe work that will enable the analysis of collected data to efficiency loss model. A polarization-based shearing interferometer is used to detect the distorted laser wave-front and reconstruct the wave-front after propagates through a 1Km near-ground atmospheric channel. Further, the heterodyne efficiency of the optical heterodyne reception system would be given under special consideration of the mismatch between the signal field and the local oscillator. By analyzing the optical heterodyne efficiency data and the real-time atmospheric coherence length data, a mathematical model of the heterodyne efficiency loss is given, which would meet the need for the description of turbulence in terms of its impact on FSO.

8874-18, Session 5

Underwater wireless optical communication using LED *(Invited Paper)*

Shlomi Arnon, Vladimir Pilipenko, Etai Rosenkrantz, Ben-Gurion Univ. of the Negev (Israel)

In recent years the need for high data rate underwater wireless communication (WC) has increased. Nowadays, the conventional technology for underwater communication is acoustic technology. However, the maximum data rate that acoustic technology can provide is below 1Mbps. Therefore, underwater optical WC has been proposed as an alternative, which could provide high data rate for short distances. The distance limitation of optical technology is due to the high attenuation of underwater environment. Nonetheless, the wavelengths that provide minimum attenuation are the blue-green light in the visible spectrum. In order to reduce cost and increase demand of underwater optical WC systems, the use of a blue LED has been proposed. The proposal is a result of the fact that LED offers low cost, high efficiency, reliability and compactness. However, there are some challenges to incorporate LED as part of the optical transmitter, such as low modulation rate and high non linearity. In this paper, we present measurement of non linearity and transfer function of blue LED. In addition, we discuss these challenges in a realistic scenario of underwater WC.

8874-19, Session 5

New technologies in underwater optical acquisition and tracking providing new possibilities for laser communication

Marco Tausendfreund, Cassidian Optronics GmbH (Germany)

Underwater communication has mainly been driven by the Navy under specific circumstances and challenges. Currently used here are conventional technologies using acoustic transmission, which can only realize data rates up to several kilobits. From the perspective of the operators of a submarine there is a logical prioritization towards covert operation against an evolution in data rates.

A completely different situation comes up by the use of UUVs, that create new potentials in the field of reconnaissance but one is also confronted with new problems coming up. With the development of optical sensors through to HD technology, that do not stop on the water surface, these underwater drones are indeed used for various purposes, but is an issue that data transfer in the Mbit range to a reference buoy or a submarine is just possible over a fiber optic connection. The risk of breaking of such a cable is extremely high when maneuvering the UUV.

On distances that are common for the operation by glass fiber, optical communication provides the better alternative. From the experience taken in space applications and the subsequent development of various terrestrial systems through the recent years, together with the German Naval Research Center experiments were repeated to verify the added

value of this technology. Therefore ranges of optical communication underwater were evaluated for all occurring underwater visibilities worldwide.

Largest caused problems so far is the first acquisition under water as well as the mutual optical tracking, since under water at adequate pressure no gyro-stabilized platforms can be used. Cassidian Optronics has developed and patented special optical methods, wherein based on the combined use of a modulated retro-reflector and a 4-quadrant detector underwater these difficulties can be overcome. The report describes the underlying process and thereby gives an outlook on the possibilities opened up.

8874-20, Session 5

The recovery of LED diode optical spectrum

Jan Vitasek, Jan Latal, Petr Siska, Jan Skapa, Martin Papes, Vladimir Va?inek, Technical Univ. of Ostrava (Czech Republic)

White power LED diodes could be used for illumination of rooms. These power LED diodes could be modulated too, so they could transmit data. The power LED diodes could be used for illumination and communication at the present time. The great problem of white power LED diodes is that they are limited in modulation rate because the light is generated by chemical reaction between blue light and yellow luminophore. The way, how to increase the modulation rate, is as follows. The narrow part of white power LED diode spectral characteristics is suppressed by optical filter. The suppressed part is then recovered by other LED diode, call as communication LED diode. The final optical spectrum should be as an original spectrum of white power LED diode. Now, only the communication LED diode is modulated. It could be construct a transmitter which provides an illumination and communication at the same time. This article deals with recovery of original spectrum of white power LED diode.

8874-21, Session 5

Measurements and modeling of resolved laser radiometry in the maritime environment

John S. deGrassie, Ike Bendall, Jason W. Cole, Galen Cauble, Space and Naval Warfare Systems Ctr. Pacific (United States)

A model for predicting the radiometry for a resolved laser scattering in the maritime atmosphere has been developed in the Electro-Optics group in Atmospheric Propagation Branch of SPAWAR Systems Center, Pacific. The model predicts the power received at a sensor from the local meteorological conditions of the atmosphere. Field experiments conducted in San Diego, CA allowed an opportunity to validate the predictions of the model. Radiometric calibrations of a CCD camera provided power measurements of a resolved laser to be taken from various senor-laser beam orientations. The performance of the laser scattering model is assessed from the field measurements.

8874-23, Session 6

Using speckle imaging techniques as a starting point for MFBD scene reconstruction from long horizontal-path, turbulence-degraded imagery *(Invited Paper)*

Jeremy P. Bos, Glen Archer, Michael C. Roggemann, Michigan Technological Univ. (United States)

In recent works presented at this conference we have detailed our work on quantitatively evaluating the performance of image reconstruction methods applied long horizontal path imaging scenarios through turbulence. Our work has focused on two image-processing methods, speckle imaging and methods based on Multi-Frame Blind Deconvolution (MFBD). In recent presentations, the performance of the bispectrum and Knox-Thompson phase recovery methods were compared quantitatively using simulated images sets of an object observed over a long (1000m) horizontal path through the atmosphere. In a separate presentation, the performance of a MFBD method was evaluated using similar methods. Our initial MFBD algorithm used the ensemble average of the centered image frame set as a starting for the MFBD algorithm. In this work, iteration using the MFBD begins with the scene estimate provided via speckle imaging methods (both Knox-Thompson and bispectrum phase recovery methods are explored). As with our previous work, performance is evaluated in terms of the MSE in normalized intensity value per pixel compared to a diffraction-limited reference image. We have found that an additional 4% reduction in MSE is available compared to images recovered using speckle imaging techniques alone. This technique also results in images with a lower MSE (as much as 7%) compared to using the average image as a starting point when the same exit conditions are used. In addition to residual MSE other performance metrics such as processing time and noise immunity will also be discussed.

8874-24, Session 6

Simulating video through turbulence

Kevin McBryde, Kristofor Gibson, SPAWAR Systems Ctr. (United States)

Atmospheric turbulence can cause significant degradation to video over long horizontal paths. The refractive index fluctuations along the path from scene to camera lead to blur, varying across the frame and from frame to frame. Computationally inexpensive methods model this effect with an MTF blur function; however this technique neglects anisoplanatic effects. Wave optics techniques have been developed taking into account anisoplanatism, but ignoring scintillation, and spatial and temporal effects.

Since long horizontal paths over varied surfaces (e.g. water to land or vice versa) will encounter varying turbulence strength along the path, the turbulence strength should be defined independently at each phase screen. Also important, turbulence strength can vary over short time scales (<1s), so a physically accurate simulation must allow time-dependent phase screens. We will present results of a wave optics simulation technique that includes these spatial and temporal variations. The results will provide validation for turbulence removal algorithms.

8874-25, Session 6

The feasibility of vision systems to form free-space optical links

Mohammed A. Eslami, Ching-Hui Chen, John Rzasa, Stuart D. Milner, Christopher C. Davis, Univ. of Maryland, College Park (United States)

Active systems and raster scans are the most popular methods for achieving the pointing accuracy required to form an optical link. With advances in vision system technology, a potential extension to current methods of alignment is to use cameras to control coarse and/or fine pointing acquisition and tracking to establish optical communication links. Using a stereo-setup to localize a target's 3D location is of great benefit to find the appropriate pointing settings to establish such links. The narrow beam widths of an optical link require very accurate calibrations of the camera's intrinsic (focal length, skew, distortions) and extrinsic (pose and orientation) parameters to provide a proper mapping between the 3D world coordinate and a 2D pixel coordinate for proper pointing. Currently, the most widely used calibration schemes use the pinhole model of a camera – which optically translates to a smaller aperture that captures only chief rays from the target – to extract the intrinsic and extrinsic parameters. In this paper, a model is presented to analyze the effects of focal length and principal point deviation on the achievable pointing accuracies. The effects of radial distortion from a lens on the achievable pointing accuracies are also presented.

8874-26, Session 6

Propagation of J0-Bessel correlated beams in weak atmospheric turbulence

O. Korotkova, Univ. of Miami (United States); Charles Nelson, Svetlana Avramov-Zamurovic, Daniel J. Whitsett, J. Watkins, Reza Malek-Madani, U.S. Naval Academy (United States)

When a partially coherent beam propagates through a turbulent medium, at relatively short distances from the source, it generally exhibits lower scintillation index in comparison to that of a comparable coherent beam.

Optimal intensity shaping and reduction in the scintillation index are of great importance to the wave propagation in maritime environment due to the significant impact of random medium on the effective delivery of energy on the target. At the United States Naval Academy, we have been successfully generating various random beams of Schell type using a nematic, phase-only spatial light modulator (SLM) and propagating them along paths set in different turbulent conditions. The latest experiments involving J0-Bessel correlated Schell-model beams have shown interesting propagation properties compared to those for the other beam classes. The conference presentation will cover the results of generation and propagation over the several hundred-meter link for both classic Gaussian Schell-model beams and J0-Bessel correlated Schell-model beams with wide range of source coherence states. For such beams, the reduction in the scintillation index has been demonstrated reliably.

8874-27, Session 6

Detection of non-standard atmospheric effects in FSO systems

Juraj Poliak, Otakar Wilfert, Brno Univ. of Technology (Czech Republic)

Modern free-space optical (FSO) communication systems in many aspects overcome wire or radio communications. They offer a license-free operation and a large bandwidth. Operation of outdoor FSO links struggles with many atmospheric phenomena that deteriorate phase and amplitude of the transmitted optical beam. Thanks to the recent advancing development, these effects are more or less well understood and described. Goal-driven research increased the link availability.

Besides increasing the availability of data links it is necessary to focus on the accuracy and reliability of testing optical links. Research of the data optical links is focused on the transmission of a large amount of data whereas the testing FSO link is designed to achieve maximal resolution and sensitivity thus improving accuracy and repeatability of the atmospheric effects measurement. Given the fact that testing links are located in the measured media, they are themselves influenced by it. Phenomena such as the condensation on transceiver windows (rain, frost) and the deviation of the optical beam path caused by the wind are referred to as non-standard effects. Non-standard effects never occur independently; therefore we must always verify the cross-sensitivity of the testing link.

In the paper we respond to an increasing number of articles dealing with influence of the atmosphere on the link but ignoring the cross-sensitivity of the testing link on other variables than tested. In conclusion, we carry out qualitative and quantitative analysis of self-identified non-standard effects.

8874-28, Session 7

Improved sparse spectrum model for the turbulent phase *(Invited Paper)*

Mikhail I. Charnotskii, National Oceanic and Atmospheric Administration (United States)

Recently published Sparse-Spectrum (SS) model of the phase front perturbations by atmospheric turbulence [M. Charnotskii, JOSA A, 30 479-488 (2013)] is based on the trigonometric series with discrete random support. SS model offers substantial savings of the computational efforts, while preserving the wide range of scales typically associated with turbulence perturbations. We present an improved version of the SS model that accurately reproduces the power-law spectral density of the phase fluctuations in the required spectral band that can be as wide as six orders of magnitude in each direction. SS model offers a substantial flexibility in the choice of the probability distributions of the wave vectors of the individual spectral components while preserving the prescribed second statistical moment including the spectrum. We use the Monte-Carlo model to examine the higher-order statistics of the SS phase samples. The number of spectral components and the degree of overlapping used in the model are the primary parameters affecting the SS phase statistics. We also present the calculations of the practically important long-exposure and short-exposure Strehl numbers for the different versions of the SS model, and discuss the long-term and short-term scintillations in the image of the point source.

8874-29, Session 7

Calculating phase shifts using a bubble model for free-space optical communication links

Heba Yuksel, Demet Yuksel, Bogaziçi Üniv. (Turkey)

Atmospheric turbulence has a significant impact on the quality of a laser beam propagating through the atmosphere over long distances. Turbulence causes intensity scintillation and beam wander from propagation through turbulent eddies of varying sizes and refractive index. This can severely impair the operation of target designation and Free-Space Optical (FSO) communications systems. In addition, experimenting on an FSO communication system is rather tedious and difficult. The interferences of plentiful elements affect the result and cause the experimental outcomes to have bigger error variance margins than they are supposed to have. Especially when we go into the stronger turbulence regimes the simulation and analysis of the turbulence induced beams require delicate attention. We propose a new geometrical model to assess the phase shift of a laser beam propagating through turbulence. The atmosphere along the laser beam propagation path will be modeled as a spatial distribution of spherical bubbles with refractive index discontinuity calculated from a Gaussian distribution with the mean value being the index of air. For each statistical representation of the atmosphere, the path of rays will be analyzed using geometrical optics. These Monte Carlo techniques will assess the phase shift as a summation of the phases that arrive at the same point at the receiver. Accordingly, there would be dark and bright spots at the receiver that give an idea regarding the intensity pattern without having to solve the wave equation. The Monte Carlo analysis will be compared with the predictions of wave theory.

8874-30, Session 7

Geometrical optics analysis of atmospheric turbulence

Chensheng Wu, Christopher C. Davis, Univ. of Maryland, College Park (United States)

Atmospheric turbulence has a significant effect in reducing system performance in long range free space optical (FSO) communications. Atmospheric turbulence causes cumulative distortion of propagating beam waves, causing their constituent light rays to deviate from straight line paths, which results in intensity redistribution at the plane of the receiver. The analysis of the received field is traditionally carried out with wave analysis using phase screens and Kirchoff-Fresnel diffraction analysis. However, since the smallest diffracting structures (eddies) in the atmosphere are much larger than the wavelength, a geometrical optical analysis should be able to provide substantial information. We have previously shown that such an analysis correctly predicts beam wander and aperture averaging effects. We have modeled the atmospheric turbulence as a collection of curved interfaces with refractive index discontinuities or as a collection of spherical bubbles with distributed sizes, positions, and refractive indices. This method, though reasonable in mimicking the reality, consumes enormous computational resources to acquire considerable accuracy in simulating and estimating the impact of atmospheric turbulence. We have developed a much more manageable approach to evaluating the turbulence effects on FSO systems by using linearized segments of light ray trajectories to represent real curved light rays. Thus the gradually shifted wave fronts are simulated by a number of integrated reflections distributed randomly inside the channel. In our approach, air bubbles are equivalently replaced by a large number of tiny mirrors with random orientations that mimic different magnitudes of turbulence. As a result, these tiny mirrors set up statistically in a Monte Carlo simulation lead to the same conclusions predicted by established theories, such as the (Range)3 dependence of beam wave mean-squared wander, aperture averaging, the breakup of beams, and reduced coherence of the beam wave. This random-walk approach to the passage of light rays through a turbulent medium allows the analysis of a model where the turbulence is continuously distributed rather than collapsed into phase screens.

8874-31, Session 7

Understanding spatial diversity using a geometrical model for optical wireless applications

Heba Yuksel, Demet Yuksel, Bogaziçi Üniv. (Turkey)

Ways of calculating phase shifts between laser beams propagating through atmospheric turbulence can give us insight towards the understanding of spatial diversity in Free-Space Optical (FSO) links. We propose a new geometrical model to estimate phase shifts between rays as the laser beam propagates through a simulated turbulent media. Turbulence is simulated by filling the propagation path with spherical bubbles of varying sizes and refractive index discontinuities statistically distributed according to various models. The level of turbulence is increased by elongating the range and/or increasing the number of bubbles that the rays interact with along their path. For each statistical representation of the atmosphere, the trajectories of two parallel rays separated by a particular distance are analyzed and computed simultaneously using geometrical optics. The three-dimensional geometry of the spheres is taken into account in the propagation of the rays. The bubble model is used to calculate the correlation between the two rays as their separation distance changes. The total distance traveled by each ray as both rays travel to the target is computed. The difference in the path length traveled will yield the phase difference between the rays. The mean square phase difference is taken to be the phase structure function which in the literature, for a pair of collimated parallel pencil thin rays, obeys a five-third law assuming weak turbulence. All simulation results will be compared with the predictions of wave theory.

8874-32, Session 8

On modeling and simulating controls and predicting network instabilities in mobile directional wireless networks

David M. Coleman, Stuart D. Milner, Christopher C. Davis, Univ. of Maryland, College Park (United States)

Research in mobile directional wireless backbone (DWB) networks has yielded technological advances in free-space optical and directional RF link performance. However, there has been a lack of research on the performance of these links in a DWB. We have addressed this need by developing network control models and by customizing modelling and simulation software for testing their effectiveness in an internet using OPNET and MATLAB. We introduce correct physical models for FSO and RF links, augment the medium-access control layer for true narrow-beam point-to-point links, and introduce a new layer in the Internet Protocol stack for the control in mobile DWB networks. We provide a customized modelling and software platform, which will extend simulations beyond single-link and relay performance and in the direction of full mobile DWB networks. In addition, we extend our novel analogy between a mobile DWB network with molecular dynamics to achieve a reduced penalty during link disruption events (including full partitions) and ultimately predict unstable configurations. In this approach, we model the effects of end-user mobility, platform geometries/dynamics, terrain, and obscuration as catalysts in the environment of the mobile DWB network, which invoke a link disruption event or more severely a network reconfiguration. This effort yields an analysis of the network on the order of minutes prior to a network reconfiguration and is obtained through inherent properties of the aggregate network (not from individual link performance) through normal mode analysis.

8874-33, Session 8

Capacity maximizing precoder design for a MIMO optical wireless channel using RGB LEDS

Qian Gao, Gang Chen, Univ. of California, Riverside (United States)

In this paper, we consider the problem of precoder design for an optical wireless communication system employed with multiple transmitters and receivers. In our intensity modulated (M) system, each transmitter contains a red-green-blue light emitting diode (RGB LED) array. For detection purpose, imaging devices are used so that the LED arrays are imaged onto the detector arrays, which are combined with color filters to provide independent RGB tunnels. We show that the resulting channel matrix between LED and detector arrays is of full rank. thus multiple finite-alphabet data streams can be modulated onto the LED arrays simultaneously. We then formulate an optimization problem targeted at maximizing the system capacity by searching for the linear precoding matrix which optimally rotates the data symbols, allocates powers, and loads the beams along the channel eigenvectors. The design constraints includes: the average optical power constraint, the non-negative real intensity constraint, and several lighting constraints such as the color rendering, luminous efficacy, and flickering-free. The supremacy of multi-color over monochrome, precoded over uncoded, and multiplexing over spatial modulated systems are elaborated with the simulation and experimental results as evidences.

8874-34, Session 8

Spatial modulated color shift keying and constellation design

Qian Gao, Tian Lang, Gang Chen, Zening Li, Univ. of California, Riverside (United States)

In this paper, we propose a scheme called spatial modulated color shift keying (SM-CSK), a promising candidate supporting high speed transmission of VLC which uses multiple red/green/blue (RGB) light-emitting diodes (LEDs) as transmitters and thus takes advantage of the diversities in wavelength and space domain. During each modulation interval, only one among N LED lights is allowed to be turned on, and binary sequences are mapped onto a constellation of size M with color basis. Therefore, log2(MN) bits get conveyed at once. We show this by simulation and experimental results which SM-CSK have higher spectrum efficiency than the widely applied optical modulation schemes: on-off-keying (OOK) and pulse position modulation (PPM). Moreover, multiple input multiple output (MIMO) has also been studied for its channel interference trade off. Taking into account the intensity modulation and direct detection (IM/DD), the luminous efficacy rate (LER) and the color rendering index (CRI) constraints, we propose a constellation design algorithm based on non-convex optimization. For a target bit error rate (BER) at 10 -9, our algorithm finds power efficient constellations offline without increasing complexity at both the transmitter and receiver side. Our result is compared to the billiard algorithm which is a pioneer work for constellation design for CSK.

8875-13, Session PMon

SILICON CARBIDE: AN ADVANCED PLATFORM FOR NEXT GENERATION QUANTUM DEVICES *(Invited Paper)*

Stefania Castelletto, RMIT Univ. (Australia); Brett C. Johnson, The Univ. of Melbourne (Australia); Albert Parker, RMIT Univ. (Australia)

Deep defects are ubiquitous in many advanced materials. Whilst for conventional applications they can be detrimental and, for many years, their effects diminished devices functionalities and performances, more recently some of these defects are found to be useful in applications such as solid state quantum computation and quantum optical communication.

Silicon carbide, due to its harbouring of optical and paramagnetic deep defects, is presently indicating the opportunity to advance and merge several areas of research, providing the means to advance quantum-physics-based devices. Its recently studied functionalities, described in this paper, could allow the implementation of several degrees of freedom quantum systems in fully integrated operational devices. The harshening of SiC advance in engineered quantum systems could also open new avenues for fundamental quantum physics research.

In particular we will show recent breakthroughs on the engineering for the first time of single photon emission in SiC monolithic crystals and nanocrystals.

8875-32, Session PMon

Non-deterministic quantum CNOT gate with double encoding

Amor Gueddana, Moez Attia, Rihab Chatta, SUP'COM (Tunisia)

We define an Asymmetric Partially Polarizing Beam Splitter (APPBS) to be linear optical component having different reflectivity (transmittance) coefficients, on the upper and the lower arms, for horizontally and vertically Polarized incident photons.

Our CNOT model is composed by two APPBSs, one Half Wave Plate (HWP), two Polarizing Beam Splitters (PBSs), a Beam Splitter (BS) and a pi-phase rotator for specific wavelength.

Control qubit operates with dual rail encoding while target qubit is based on polarization encoding.

To perform CNOT operation in 4/27 of the cases, input and target incoming photons are injected with different wavelengths.

8875-33, Session PMon

Towards the demonstration of interference between single photons from independent Ni:diamond Lattice and SPDC sources

Oliver T. Slattery, National Institute of Standards and Technology (United States) and Univ. of Limerick (Ireland); Paulina Kuo, Yong-Su Kim, Xiao Tang, National Institute of Standards and Technology (United States); Igor Aharonovich, Univ. of Technology Sydney (Australia); Stefania Castelletto, RMIT Univ. (Australia) and ARC Ctr. for Engineered Quantum Systems (Australia)

The production of verifiably indistinguishable photons from independent sources is a critical element in the application of long distance quantum communications. Observation of Hong-Ou-Mandel (HOM) interference of single photons is a common technique to verify such indistinguishability. Nickel-related color centers in diamond (Ni:diamond) have been identified as a good sources of single photons at room temperature. Meanwhile, spontaneous parametric down-conversion (SPDC) is a well-established method for single photon pair production and can be designed for degenerate or non-degenerate pairs at wavelengths suitable for long distance communications. Here we outline an experiment that will measure the Hong-Ou-Mandel (HOM) interference between a single photon produced by SPDC and a single photon from a Ni-related defect in diamond. The independent photons exhibit different frequencies and spectral linewidths and therefore require spectral engineering to achieve successful Hong-Ou-Mandel interference. We propose to use a non-linear frequency upconversion scheme to match the SPDC photon to the frequency of the photon from the Ni:diamond while preserving the single photon statistics of the source. The upconversion process also serves as a narrow bandpass filter of the broadband SPDC photons. Therefore, tunable narrow bandpass filtering of the photons from the Ni:diamond will be required to ensure indistinguishability of the photons from each source. We propose to use a volume Bragg grating to suitably filter the photons from the Ni:diamond. Independent single photon sources can facilitate hybrid quantum communications schemes and advance the state of quantum communications.

8875-34, Session PMon

Multidimensional ghost imaging

Ronald E. Meyers, U.S. Army Research Lab. (United States)

No Abstract Available

8875-1, Session 1

New quantum imaging experiments at ARL *(Invited Paper)*

Ronald E. Meyers, U.S. Army Research Lab. (United States)

No Abstract Available

8875-2, Session 1

Quantum limits of optical super-resolution and a priori information *(Invited Paper)*

Mikhail Kolobov, Univ. des Sciences et Technologies de Lille (France)

The conventional concept of resolving power of an optical instrument was developed at the end of the nineteen century in classical works of Abbe and Rayleigh. In the framework if the modern Fourier optics the resolving power of an optical system is characterised by its spatial-frequency transmission band. Classical super-resolution is an attempt to restore the spatial Fourier components of the object outside the transmission band of the system. Such super-resolution is possible when one has some a priori information about the object, for example, that the object has a finite size.

We shall give an overview of the quantum theory of optical resolution and show that super-resolution crucially depends on the amount of a priori information about the object. We shall demonstrate that the standard quantum limit of super-resolution for discrete objects is much higher than that for continuous objects due to higher amount of a priori information. We shall prove that one can go beyond the standard quantum of super-resolution using spatially multimode squeezed light. We shall present the latest results for the quantum limits of super-resolution for sparse optical images using the compressed sensing approach.

8875-3, Session 1

Atom lithography with subwavelength resolution *(Invited Paper)*

M. Suhail Zubairy, Zeyang Liao, Texas A&M Univ. (United States); Mohammad Al-Amri, KACST (Saudi Arabia)

The resolution of optical lithography and the spacing of atom lithography are limited by about half of the wavelength due to the Rayleigh diffraction limit. Here we propose a coherent atom lithography experiment which can print nanometer structures. In this proposal, we show that sub-wavelength spatial distribution of the atom in the excited state can be achieved by inducing a spatially modulated Rabi oscillations in a two-level atom. We use the internal energy of the atom to excite the photoresist and we can then print the sub-wavelength structure into the photoresist. For the peak Rabi frequency of about 2GHz and the recoil limited collimation, we show that sub-10nm spacing is possible.

8875-4, Session 1

On using intensity interferometry for feature identification and imaging of remote objects *(Invited Paper)*

Baris I. Erkmen, Dmitry V. Strekalov, Nan Yu, Jet Propulsion Lab. (United States)

Intensity interferometry is a well-known and widely utilized technique in both classical and quantum optics, as well as in astronomy. Conventional intensity interferometry correlates the photocurrents from two pinhole detectors facing an extended thermal source, for different transverse displacements of the two detectors, obtaining an estimate of the magnitude-square of its mutual coherence function at the measurement plane. This allows one to estimate features of the source such as its diameter, or to form an image of its photon-flux density (with some regularity conditions). In this work, we focus on using this technique to identify or image an object that is in the line-of-sight between a well-characterized source and the detectors. We derive the observed perturbation to the intensity correlation map due to the object, showing that under some reasonable approximations it is proportional to the real part of the Fourier transform of the source's photon-flux density times the Fourier transform of the object's intensity absorption. We identify from this signature the key parameters that impact its visibility. We discuss the requirements for estimating object-related parameters, e.g., its size, velocity or shape, as well as the feasibility of reconstructing an image, provided that some knowledge of the source and the propagation geometry is available a priori. We consider an application of this result to determining the orbit inclination of an exo-planet orbiting a distant star. Finally, motivated by the intrinsically weak nature of the signature, we study its signal-to-noise ratio and determine the impact of system parameters.

8875-5, Session 2

Protecting quantum entanglement from amplitude damping *(Invited Paper)*

Zeyang Liao, Texas A&M Univ. (United States); Mohammad Al-Amri, KACST (Saudi Arabia); M. Suhail Zubairy, Texas A&M Univ. (United States)

Quantum entanglement is a critical resource for quantum information and quantum computation. However, entanglement of a quantum system is subjected to change due to the interaction with the environment. One typical result of the interaction is the amplitude damping that usually results in the reduction of the entanglement. Here we propose a protocol to protect quantum entanglement from the amplitude damping by applying Hadamard and CNOT gates. As opposed to some recently studied methods, the scheme presented here does not require weak measurement in the reversal process, leading to a faster recovery of entanglement. We propose a possible experimental implementation based on linear optical system.

8875-6, Session 2

Quantum optical state engineering and continuous variable entanglement enhancement *(Invited Paper)*

Adarsh S. Prasad, Roohollah Ghobadi, Christoph Simon, Aveek Chandra, Univ. of Calgary (Canada); Yury Kurochkin, Alexander I. Lvovsky, Univ. of Calgary (Canada) and Russian Quantum Ctr. (Russian Federation)

The technology of preparation of quantum states is of key importance for applications in quantum information technology, such as quantum communication, metrology and computation. Here we demonstrate two separate experiments relating to quantum state creation and continuous variable quantum state enhancement.

Our first experiments relates to Schrödinger's famous thought experiment involving a (macroscopic) cat whose quantum state becomes entangled with that of a (microscopic) decaying nucleus. Here we demonstrate conclusively for the first time the creation of such micro-macro entanglement in light. The macro system involves over a hundred million photons, while the micro system is at the single-photon level. We show that microscopic differences (in field quadrature measurements) on one side are correlated with macroscopic differences (in the photon number variance) on the other side. We demonstrate entanglement of our state by bringing the macroscopic state back to the single-photon level and performing full quantum state tomography of the final state.

In our second experiment we demonstrate an efficient experimental technique to enhance continuous variable entanglement of a two mode squeezed state. We apply a photon annihilation operator to both modes of a two mode squeezed state generated by a Type –II spontaneous parametric down-conversion. The annihilation operator is implemented using a polarization independent asymmetric beam splitter. Conditioned on simultaneous 'clicks' heralding successful photon annihilation, we employ homodyne tomography to reconstruct the resulting two mode state and verify entanglement distillation.

8875-7, Session 2

Entangled photon generation in a phase-modulated, quasi-phasematched crystal *(Invited Paper)*

Paulina Kuo, Joint Quantum Institute (United States) and National Institute of Standards and Technology (United States); Jason S. Pelc, Hewlett-Packard Labs. (United States); Oliver T. Slattery, Yong-Su Kim, Xiao Tang, National Institute of Standards and Technology (United States)

Polarization-entangled photon pairs can be generated using spontaneous parametric downconversion (SPDC) in type-II, quasi-phasematched crystals. A pair of crystals is often used to generate the |HV? and |VH? states. For this scheme, the temporal distinguishability (or "which crystal" information) must be erased in order to produce the entangled state. This temporal distinguishability can be erased by using a birefringent crystal or Michelson interferometer after the SPDC crystal. The distinguishability can also be removed during the SPDC process if the quasi-phasematching is designed to simultaneously generate the |HV> and |VH> states. We design a phase-modulated periodically poled LiNbO3 crystal for the near-degenerate SPDC process 776 nm --> 1535 nm + 1570 nm. Two type-II processes are simultaneously phasematched: |H776nm> --> |H1535nm V1570nm> and |H776nm> --> |V1535nm H1570nm>. The phase-modulation allows both states to be generated simultaneously in a distributed fashion throughout the nonlinear crystal.

Working near degeneracy makes the downconversion bandwidths nearly matched, which is needed for good entanglement visibility. The photon pair emerge collinearly but can be efficiently separated using a dichroic filter. This polarization-entangled source can be used to demonstrate violation of Bell's inequality or quantum teleportation.

8875-8, Session 3

Breaking the diffraction limit using entanglement based microscopy *(Invited Paper)*

Daniel Schlenk, Ludwig-Maximilians-Univ. München (Germany); Harald Weinfurter, Ludwig-Maximilians-Univ. München (Germany) and Max-Planck-Institut für Quantenoptik (Germany)

The resolution of optical scanning microscopes is limited by the spot size of the scanning beam. It has been proposed by Boto et al. (Rhys. Rev. Lett. 85, 2733) and Nasr et al. (Phys. Rev. A 65, 023816) that momentum entangled photons can be focused more tightly than classical light. We obtain momentum entangled photons pairs from a spontaneous parametric down conversion source in our confocal microscope setup to demonstrate a two-photon spot size below the classical diffraction limit.

Momentum entangled photon pairs at a center wavelength of 812 nm are created in a BBO-crystal cut for type I collinear down conversion which is pumped by a laser diode with a wavelength of 406 nm. An objective with a numerical aperture of NA=1.4 is used to focus the photon pairs. In the confocal setup light reflected from an object is collected with the same objective used for illumination and separated from the incoming light with a 50/50 beam splitter. Two avalanche photodiodes behind a second 50/50 beam splitter detect photons reflected from the object and allow to measure the single and two-photon detection probabilities for reflected photons.

As a test object a single gold stripe deposited on a glass surface is moved through the focused beam to determine the resolution of this microscope. We obtained a two-photon spot size of 194 nm FWHM which is well below the classical diffraction limit of 295 nm for 812 nm photons and even breaks the two-photon spot size limit of 209 nm FWHM.

8875-9, Session 3

Superresolving power quantum microscope using ghost imaging technology *(Invited Paper)*

Sanjit Karmakar, Univ. of Maryland, Baltimore County (United States); Ronald E. Meyers, U.S. Army Research Lab. (United States); Yanhua Shih, Univ. of Maryland, Baltimore County (United States)

Research and development are progressing very rapidly in different areas of biomedical and biosciences. Biomedical imaging is one of these exciting important areas. Super resolving power, non-invasive camera with a feature of not damaging any cell or tissue enables physicians and scientists to see and better understand tissue and organ function. Using two-color ghost imaging technology, we wish to propose a camera capable of achieving very high resolving power, i.e. super resolving power, without any destruction of cells and tissues.

In an experimental configuration of two-color ghost imaging entangled photon pairs with ?s > ?i generated from spontaneous parametric down-conversion (SPDC) reproduce a ghost image with enhanced resolving power by a factor of ?s / ?i by means of higher imaging amplification which is enhanced by a factor of ?s / ?i than that of the one-color ghost imaging as well as the classical imaging set up, where ?s is the wavelength of the radiation that illuminates the object, ?i is the wavelength of idler beam. If one can use ?s (? 500 nm) in the visible region and ?i in the x-ray region (? 1 nm), then resolving power can be improved by a factor of 500.

In case of the one-color ghost imaging as well as the classical case, we can resolve few µm with visible light. The size of human cell and tissue are of the order of µm. This proposed technique can improve the resolving power by a factor of 500 than the usual one-color ghost imaging and the classical case. Also, in this configuration the cell and tissue are illuminated by the visible light instead of x-ray and hence there is no chance of destruction of the cells and tissues.

8875-10, Session 3

Toward sub-wavelength lithography with atomic coherence *(Invited Paper)*

Philip R. Hemmer, Texas A&M Univ. (United States)

There has been much interest in the possibility of using optical or quantum nonlinearities to perform sub-wavelength lithography. Techniques that have been proposed so far include quantum N00N states, Dopplerons, Raman dark states, light shifts (in gradient fields), and Rabi flops. However none of these coherent or quantum techniques have yet demonstrated the ability to expose photoresist with a resolution and aspect ratio better than incoherent techniques like optical donut-beam lithography. But this is a serial step-and-repeat exposure protocol much like e-beam lithography, and hence is not very convenient for exposing large areas. In this talk I will review our current progress in super-resolution optical lithography using the analog to magnetic resonance imaging in two level transitions in solid state hosts. The first system is nitrogen-vacancy (NV) diamond. It has both optical and microwave transitions that are suitable for coherent lithography. In the case of the microwave transitions, room temperature operation is possible. The second system is rare earth doped crystals like Pr doped YAG or YSO. Here there is potential for using a two-photon transition to transfer the optical super-resolution pattern to a UV transition that can more easily expose photo-resist. The relative merits and unsolved problems of these two systems will be discussed.

8875-11, Session 3

Quantum measurements and sensings *(Invited Paper)*

Shigeki Takeuchi, Hokkaido Univ. (Japan)

In this invited talk, we will report our recent progresses on quantum measurements and sending.

Optical phase measurement is a key technology in many kinds of metrology. The accuracy of the measurement for a given light intensity, or the number of photons, is limited by the standard quantum limit. However, recently it has been demonstrated that the standard quantum limit can be beaten by using entangled photons.

In this presentation, we report the first demonstration of an entanglement microscope, which is the differential confocal microscope where an entangled photon pair source is used for illumination. We show that the S/N ratio of the image obtained by the entanglement microscope is 1.35 times better than that limited by the standard quantum limit. This experimental demonstration will open the door for the broad application of entanglement-enhanced metrology from biology to material science.

We will also report other topics on quantum measurements and sensing, including the experimental demonstration of the dispersion-tolerance of the quantum optical coherence tomography in the high resolution regime, and adaptive quantum state estimation of single photon quantum bit, and discuss the advantages of AQSE to currently used quantum state tomography.

8875-12, Session 4

Aqueye Plus: a very fast single photon counter for simultaneous multicolor astronomical photometry equipped with an optical vortex coronagraph *(Invited Paper)*

Cesare Barbieri, Giampiero Naletto, Mirco Zaccariotto, Elettra Mari, Enrico Verroi, Anna Sponselli, Filippo Romanato, Univ. degli Studi di Padova (Italy); Luca Zampieri, INAF - Osservatorio Astronomico di Padova (Italy); Tommaso Occhipinti, Adaptica S.r.l. (Italy)

In recent years we developed two very high speed single photon photometers, Aqueye and Iqueye (Naletto el al. 2009, Barbieri et al. 2012) as prototypes for 'quantum' photometers for the Extremely Large Telescopes of the next decade. The instruments, based on single photon avalanche photodiodes (SPAD) and a 4-fold split-pupil concept, have been successfully used to obtain data of the highest quality on optical pulsars (Gradari et al., 2011, Germana' et al., 2012). Subsequently, we performed an attempt to utilize the Orbital Angular Momentum and associate Optical Vorticity to achieve high performance coronagraphy (Mari et al., 2012). Presently, we are building Aqueye Plus for the 1.8m telescope of the Asiago - Cima Ekar Observatory, a new instrument which combines both functions, namely high speed simultaneous multicolor photometry and coronagraphy. The innovative capability of Aqueye Plus is to take advantage of the two parallel outputs (NIM and TTL) of the four SPADs. The NIM output preserves the best timing capability, the TTL output drives a deformable 32-element mirror in a sort of quadrant detector to correct for defocus, tip/tilt and low order aberrations of the stellar image on the phase mask discontinuity. The concept has been already used for free space quantum communication experiments (Capraro et al., 2012). The phase mask (Massari et et al.,2011) has 512 steps and is tailored to 530 nm wavelength.

The paper will describe the instrument and its first results in the laboratory.

8875-14, Session 4

Phase retrieval near 2 bits/photon using a heralded single-photon source *(Invited Paper)*

Reihaneh Shahrokhshahi, Niranjan Sridhar, Univ. of Virginia (United States); Saikat Guha, Raytheon BBN Technologies (United States); Aaron Miller, Albion College (United States); Adriana Lita, National Institute of Standards and Technology (United States); Brice Calkins, Albion College (United States); Thomas Gerrits, Antia Lamas-Linares, National Institute of Standards and Technology (United States); Jonathan L. Habif, Raytheon BBN Technologies (United States); Sae Woo Nam, National Institute of Standards and Technology (United States); Olivier Pfister, Univ. of Virginia (United States)

We report progress towards information-efficient quantum imaging. We implemented a 4-mode interferometer which uses both polarization and spatial encoding to image Hadamard-encoded phase arrays. This demonstration is a particular case of a generalized M-path interferometer which can yield log_2(M) bits of information with a single measurement of a single photon, the photon being placed in a W state over the different arms of the interferometer.

In the ideal, lossless case, any single-mode, pure-state or mixed quantum input in the interferometer will appear unchanged at either one of the 4 output ports, depending on the Hadamard phase codeword in the interferometer (which is a combination of 0 and pi phase shifts). The Photon Information Efficiency (PIE) is then log_2(4)/< N>, where < N> is the average photon number.

For an arbitrary quantum state with rho=sum_n p_n |n>< n|, PIE=log_2(4)/(sum_n n p_n).

The photon-number-resolving ability of transition edge sensors thus allowed us to directly measure p_1 and p_2 and to evaluate the PIE. A maximum PIE of 2 bits per photon (bpp) for the above mentioned interferometer can be achieved by preparing a perfectly heralded single photon source, with < N>=1 and g^(2)(0)=0, as input of the interferometer.

In our experiment, we achieved the construction of a highly quantum heralded single photon source with g^(2)(0) =0.03 and achieved PIE=1.97 bpp, with a non-zero probability of error. Currently efforts are underway to reduce losses and increase the heralding ratio of the single photon source to decrease the error.

8875-16, Session 4

BEC expansion and interferometry in microgravity *(Invited Paper)*

Vincenzo Tamma, Wolfgang Zeller, Albert Roura, Wolfgang P. Schleich, Univ. Ulm (Germany)

Interferometry with expanding BEC in microgravity can be exploited to probe fundamental physics at the border between quantum mechanics and general relativity. In particular, by using an asymmetric Mach-Zehender configuration interference fringes for expanding BEC in microgravity have been recently observed in pioneering QUANTUS experiments [1].

We describe the physics behind the BEC expansion and interference in microgravity in the time-dependent Thomas-Fermi (TF) regime [2,3] in generic interferometric configurations. We provide physical insight into the validity of the TF approximation depending on the experimental conditions. Moreover, we demonstrate how first order perturbation theory leads to space-dependent corrections to the BEC fringe spacing which may be fundamentally important in future metrology experiments.

The QUANTUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50WM1136.

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8875-17, Session 5

Some recent progresses in quantum tomography realised at INRIM *(Invited Paper)*

Marco Genovese, Istituto Nazionale di Ricerca Metrologica (Italy); Ivo P. Degiovanni, Istituto Elettrotecnico Nazionale Galileo Ferraris (Italy); Marco Genovese, Marco Gramegna, Fabrizio Piacentini, Ivano Ruo Berchera, Istituto Nazionale di Ricerca Metrologica (Italy)

The rapid development of quantum systems has enabled a wide range of novel and innovative technologies, from quantum information processing to quantum metrology and imaging, mainly based on optical systems.

Precise characterization techniques of quantum resources, i.e. states, operations and detectors play a critical role in development of such technologies.

In this talk, after a short summary of our past works in the field (as on-off reconstruction), we will present few recent experiments related to quantum tomography related to photon number resolving (PNR) detectors realised at INRIM: three addressed to reconstruct the POVM of PNR detectors, one considering a simple method for reconstructing mode occupation.

In the first case [1] we will discuss the reconstruction of a TES POVM based on the use of a quorum of coherent states.

In the second case [2] we present the first experimental characterization of quantum properties of an unknown PNR detector, a detector tree, that takes advantage of a quantum resource, i.e. an ancillary state. This quantum-assisted reconstruction method requires no prior information about the detector under test, and its convergence is more stable and faster to reach a final result. This is achieved by exploiting strong quantum correlations of twin beams generated in a parametric down conversion process: one beam is characterized by a quantum tomographer, while the other is used to calibrate the unknown detector.

Then, we will discuss the experimental realisation a self consistent quantum tomography of a PNR detector POVM and its application [3].

Finally, we present a work where we experimentally demonstrate the reconstruction of the mode structure of several quantum optical fields by exploiting a PNR detector.

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[3] G.Brida et al., work to be submitted.

[4] G. Brida et al, work submitted.

8875-18, Session 5

Protecting entanglement from decoherence using weak measurement and quantum measurement reversal *(Invited Paper)*

Yong-Su Kim, Jong-Chan Lee, Osung Kwon, Yoon-Ho Kim, Pohang Univ. of Science and Technology (Korea, Republic of)

Decoherence, which causes degradation of entanglement and in some cases entanglement sudden death, is a critical problem in quantum information. Protecting entanglement from decoherence, therefore, is essential in practical realization of quantum computing and quantum communication protocols. In this talk, I will describe our recent work on protecting entanglement from amplitude damping decoherence via weak measurement and quantum measurement reversal.

8875-20, Session 5

Anomalous g2 values *(Invited Paper)*

Ron Folman, Ben-Gurion Univ. of the Negev (Israel)

g2 is perhaps one of the most calculated and measured observable in quantum optics. It has given rise to numerous insights. Here we calculate the value of g2 (in the time domain) under new experimental conditions and find an anomalous behavior of this observable.

8875-21, Session 6

The role of quantum memory in quantum information processing *(Invited Paper)*

Kae Nemoto, Ashley M Stephens, National Institute of Informatics (Japan); Keith A Harrison, National Institute of Informatics (Japan) and Kismet Institute (United Kingdom); William J Munro, National Institute of Informatics (Japan) and NTT Basic Research Laboratories (Japan)

Until recently, it had been believed that long-lived quantum memory was necessary for long-distance quantum communications. Using error correction codes in an efficient way against photon loss, it is possible to transmit quantum information over a long distance without quantum memories. For quantum computation, the recent architectures of topological quantum computation indicate that the simplest structure could be memory-less.

A quantum memory is no longer an essential resource for quantum networks, however as it is in our current computer, it nonetheless could be a key device in the development of quantum information technology. It is still not clear what functional device could bring what benefits to our quantum informational systems. This is largely due to the lack of detailed models for quantum information systems.

Recently we have developed a detailed model for quantum network from a device design for building blocks to the system architecture. The device is based on optical cavity with an NV diamond center. This model naturally integrates quantum communication to computation most suitable for quantum communication, and using this model, we can discuss the cost of quantum memory effect in the processes. With or without quantum memory, it is necessary for us to be able to preserve quantum information for a long period of time in either communication or computation. The function of quantum memory can be then assessed quantitatively.

8875-22, Session 6

Verification of light shift blockade via collective state Raman-Rabi oscillations for ensemble based quantum computing *(Invited Paper)*

Selim M. Shahriar, May Kim, Yanfei Tu, Resham Sarkar, Northwestern Univ. (United States)

Recently, we have been exploring the feasibility of realizing a quantum computer using ensembles of atoms as deterministic qubits. In contrast with single atom quantum bits, this process has the potential advantage of a very high vacuum Rabi frequency, thus enabling the use of a large cavity that can accommodate many qubits held by dipole force traps. A key requirement for this process is the so-called light-shift imbalanced induced blockade (LIB), which restricts higher order transitions in the collective excitation of an ensemble of atoms so that the ensemble behaves effectively as a single atom. Here, we present a technique for demonstrating LIB using Raman-Rabi oscillations in a lambda system, via coincidence detection in a Hanbury-Brown-Twiss setup. We will describe results of numerical simulations, and present details of our experimental efforts towards this demonstration.

8875-23, Session 6

A hybrid quantum system of atoms trapped on ultrathin optical fibers coupled to superconductors *(Invited Paper)*

Steven Rolston, Jeff Grover, Univ. of Maryland, College Park (United States); Jonathan Hoffman, Joint Quantum Institute (United States); Sylvain Ravets, Kristen Voigt, Jongmin Lee, Jared Hertzberg, J. R. Anderson, Luis Orozco, Fred Wellstood, Chris Lobb, Univ. of Maryland, College Park (United States)

We are developing a system using atoms trapped in the evanescent field of ultrathin optical fibers to magnetically couple to a superconducting (SC) circuit containing a SC qubit. This hybrid system can utilize the speed of the SC device, and long coherence time of the atoms. It provides coupling to photons through the fiber mode. While developing a system compatible with a cryogenic environment, we have produced tapered fibers with >99.9% transmission, and propagated higher order modes with >95% transmission. We will discuss progress and opportunities associated with the strong photon-atom coupling of these ultrathin fibers,

8875-24, Session 6

Photonic quantum computing *(Invited Paper)*

Jeremy L. O'Brien, Univ. of Bristol (United Kingdom)

Quantum information science aims to harness uniquely quantum mechanical properties to enhance measurement, information and communication technologies, as well as to explore fundamental aspects of quantum physics. Of the various approaches to quantum computing [1], photons are particularly appealing for their low-noise properties and ease of manipulation at the single qubit level [2], which also makes them appealing for other quantum technologies [3–5]. We have developed an integrated waveguide approach to photonic quantum circuits for high performance, miniaturization and scalability [6–10]. We have begun to address the challenges of scaling up quantum circuits using new insights into how controlled operations can be efficiently realised [11], and demonstrated Shor's algorithm with consecutive CNOT gates [12] and the iterative phase estimation algorithm [13]. We have shown how quantum circuits can be reconfigured, using thermo-optic phase shifters to realise a highly reconfigurable quantum circuit able to perform almost any function on two photonic qubits [14], and electro-optic phase shifters in lithium niobate to rapidly manipulate the path and polarisation of telecomm wavelength single photons [15]. We have addressed miniaturisation using multimode interference coupler architectures to directly implement NxN Hadamard operations and the 'Boson sampling problem' [16], and by using high refractive index contrast materials such as SiOxNy, in which we have implemented quantum walks of correlated photons [17], and Si [18], in which we have demonstrated generation of orbital angular momentum states of light [19]. We have begun to address the integration of superconducting single photon detectors [20] and diamond [21,22] and non-linear [23–25] single photon sources. Finally, we give an overview of recent work on fundamental aspects of quantum measurement, including a quantum version of Wheeler's delayed choice experiment [26].

8875-25, Session 7

Which-way experiment with internal degrees of freedom *(Invited Paper)*

Konrad Banaszek, Univ. of Warsaw (Poland); Pawel Horodecki, Gdansk Univ. of Technology (Poland); Micha? Karpi?ski, Czes?aw Radzewicz, Univ. of Warsaw (Poland)

We present an inequality relating visibility and which-way information for a particle equipped with an internal degree of freedom travelling through a Mach-Zehnder interferometer. The inequality paints an unexpectedly intricate picture of wave-particle duality in the general case. Strikingly, in some instances which-way information becomes erased by introducing classical uncertainty in the internal degree of freedom. Furthermore, even imperfect interference visibility measured for a suitable set of inputs can be sufficient to infer absence of which-way information.

8875-26, Session 7

Sub-shot noise measurements with an acousto-optic modulator *(Invited Paper)*

Jason P. Simon, Yanhua Shih, Univ. of Maryland, Baltimore County (United States)

The need for high precision measurements continues to increase at an incredible pace. It is a problem in all areas of research, from communication to sensing, etc. The solution is ultimately rooted in understanding and overcoming the shot noise limit. One method of doing so is by tailoring the quantum fluctuations of a light beam so the fluctuations in the observable of interest are "squeezed", the so called squeezed states of light. Both theoretically and experimentally, nonlinear interactions have been extremely successful in generating squeezed states with squeezing well below the shot noise limit. Yet, we continue to seek after a solution to the shot noise problem.

We wish to discuss an experiment that uses an acousto-optic modulator(AOM) to over- come the shot noise limit. As is well known, the AOM can be used as a beam deflector and a frequency shifter. By orienting the AOM in a specific way, we generate two output beams, such that their frequencies and phases sum to the pump frequency and phase respectively. Furthermore, we can properly say that the output beams are correlated due to this inter- action. Then by using a dual heterodyne detection scheme, one for each output field, and measuring only the difference current from each detector, we can reproduce the squeezing effect, that so commonly defines a squeezed state. This source is useful because it relies only on a non-linear-like interaction with a strength that depends on the power of the acoustic field in the modulator.

8875-27, Session 7

Effect of decoherence in quantum reading with phase shift keying signal of entangled coherent states *(Invited Paper)*

Kentaro Kato, Osamu Hirota, Tamagawa Univ. (Japan)

Quantum reading of a classical digital memory, which was originally proposed by Pirandola, is one of attractive topics for both practical and theoretical aspects of quantum detection theory. For this problem?a quantum reading model of purely phase-encoded classical digital memory has been proposed by one of the authors and it has been shown that error-free discrimination is possible in this model under the situation that there is no channel loss. Particularly, the model employs a quasi-bell state of entangled coherent states as a probe state. Here a natural question arises: where is the error-free limit of discrimination between phase shift keying signals that is generated from an entangled coherent state when there is channel loss or other disturbance? Therefore the aim of this paper is to investigate the effect of decoherence in such a quantum reading model with phase shift keying signal of entangled coherent states. To illustrate the effect, analysis and simulations of the model will be done by using the quantum minimax strategy in quantum signal detection theory.

8875-28, Session 8

A quantum network with atoms and photons II *(Invited Paper)*

Ronald E. Meyers, U.S. Army Research Lab. (United States)

No Abstract Available

8875-29, Session 8

Software-defined quantum communication *(Invited Paper)*

Travis S. Humble, Oak Ridge National Lab. (United States)

We formalize software-defined quantum communication (SDQC) framework by considering a quantum transmitter (TX) and quantum receiver (RX). A functional decomposition of each terminal separates development concerns with respect to the hardware physics, the software protocol, and a middleware that mitigates between the other two domains. Similar decompositions can be applied to previously developed QC systems, however, our objective is to show how to identify these domains at an abstract level and develop them into concrete realizations, i.e., a top-down approach to SDQC design.

We consider a representation of the SDQC framework in which the TX hardware layer is expressed as a quantum light source for preparing quantum states and accessing the quantum channel, the middleware is represented as a hardware device driver, and the software layer is represented by a general purpose processor running user-defined

software. The classical channel is assumed to be a local area network while the quantum channel is represented by some quantum optical modes.

We further demonstrate this framework using the implementation of an entanglement distribution system. The purpose of the system is to distribute entangled qubits between the TX and RX and to validate the presence of the transmitted entanglement. In this implementation, the TX and RX monitor the visibility of the measured correlations as a form of channel diagnostic by sharing metadata over a LAN. We identify that layers within this example and give concrete description of their implementations.

8875-30, Session 8

Implementation of an m-ary three-stage quantum cryptography protocol

Mayssaa El Rifai, Nikhil V. Punekar, Pramode K. Verma, The Univ. of Oklahoma - Tulsa (United States)

This paper introduces an m-ary version of the Three-stage Quantum Cryptography protocol. The three-stage protocol was first proposed in 2006 and implemented in 2012. The three-stage protocol is a multi-photon tolerant protocol that does not require a classical channel. It uses unitary transformations known only to the sender and the receiver. Furthermore, these unitary transformations can be independently and simultaneously changed by the communicating parties. The three-stage protocol is not susceptible to the photon number splitting attacks, thus it is not subject to the requirement of no more than one photon per pulse as the BB'84 is. A recent paper discussed its implementation as a multi-photon tolerant protocol along with its security issues and proposed some security measures that should be taken. The m-ary version of the three-stage protocol presented in this paper results in enhanced data transfer rate between Alice and Bob, since each pulse carries more than one bit of information. An experimental realization of the m-ary three-stage protocol is also reported in this paper. The implementation has used free-space optics as the transmission medium and passive optical components controlled through LabView. Furthermore, analytical results that address the impact of the noise factor and its trade-off with data rate are presented. This analysis includes a study of the probability of errors and channel capacity variations in terms of the noise variance factor for the m-ary three-stage protocol using two, four and eight levels. Limits within which the m-ary three-stage protocol can be used with higher performance efficiency compared to its original version counterpart are set.

8875-31, Session 8

Hybridization of superconducting flux qubits and diamond ensembles: a route to local gates for quantum repeaters *(Invited Paper)*

William J. Munro, Xiaobo Zhu, Yuichiro Matsuzaki, NTT Basic Research Labs. (Japan); Ashley M Stephens, Kae Nemoto, National Institute of Informatics (Japan); Shiro Saito, NTT Basic Research Labs. (Japan)

Quantum mechanics was one of the most important discoveries of the twentieth century. It is a set of principles describing physical reality at the atomic level of matter and allows for radially new ways to transmit, store and process information. Quantum communication is now regarded as a primitive necessary for any future quantum internet, regardless of whether such communication is over distances of centimeters or thousands of kilometers. Over the last decade there has been a considerable worldwide effort to develop quantum repeaters – a device that allows one to extend the range in which quantum information can be transmitted. There has been a significant effort to investigate and demonstrate the fundamental building blocks necessary for such repeaters to the extent that entanglement distribution over tens of kilometers is now relatively routine. However to extend the range further we need entanglement swapping – which require local two qubits. Such gates have proved challenging and are now seen a significant performance bottleneck. Hence we need to find mechanisms to efficiently perform such gates. It is well known that superconducting flux qubits have excellent processing ability while electron-spin nitrogen-vacancy centers in diamond are a natural memory and optical interface. Hybridization of these two systems thus presents the promise of an effective and efficient way to perform such local gates. Here we report on the realization of quantum memory operations between these hybrid systems as well as the realization of quantum memory operations. This is a first step towards superconducting based gates for quantum repeaters.

8876-1, Session 1

The James Webb Space Telescope *(Invited Paper)*

Mark Clampin, NASA Goddard Space Flight Ctr. (United States)

The James Webb Space Telescope (JWST) is a large aperture (6.5 meter), cryogenic space telescope with a suite of near and mid-infrared instruments covering the wavelength range of 0.6 ?m to 28 ?m. JWST's primary science goal is to detect and characterize the first galaxies. It will also study the assembly of galaxies, star formation, and the formation of evolution of planetary systems. JWST is a segmented mirror telescope operating at ~40K, a temperature achieved by passive cooling of the observatory, via a large, 5-layer membrane-based sunshield. We present an overview of the observatory systems design, the science instruments and the mission science objectives. We will report on recent highlights such as the completion of all the mirrors in JWST optical chain, and delivery of the first two science instruments. We will also review the predicted performance of the JWST observatory, based on initial measurements of the telescope optics and instrumentation.

8876-2, Session 1

Ultrafast laser inscribed 3D integrated photonics *(Invited Paper)*

Simon Gross, Alexander Arriola, Guido Palmer, Nemanja Jovanovic, Izabela Spaleniak, Thomas D. Meany, Yuwen Duan, Qiang Liu, Peter Dekker, Macquarie Univ. (Australia); David G. Lancaster, Heike Ebendorff-Heidepriem, The Univ. of Adelaide (Australia); Alexander Fuerbach, Michael Ireland, Michael J. Steel, Michael J. Withford, Macquarie Univ. (Australia)

Since the discovery in 1996, that a tightly focused femtosecond laser beam can induce a highly localized and permanent refractive index change in bulk dielectrics, ultrafast laser inscription has found applications in a diverse range of fields. This highly localized index change is a result of nonlinear photoionization, which can be triggered in virtually any dielectric ranging from glasses to crystals and by simply moving the substrate through the focused femtosecond laser beam, 3 dimensional photonic circuits can be sculpted. The fact that these circuits are embedded within the bulk results in an inherent environmental robustness against vibrations and temperature variations. Furthermore, they can offer a high level of integration and as such can be compact and lightweight.

A crucial requirement for ultrafast laser inscription is the deeper understanding of the structural modifications that result in the refractive index change within the sample. This not only enables the appropriate choice of glass and the optimization of the fabrication parameters in order to improve the device performance but it also allows for engineering materials to tailor their properties for ultrafast laser inscription.

In this presentation we will review our current understanding of ultrafast laser – glass lattice interactions, with a particular focus on ZBLAN, phosphate and silicate glasses. We will present the application of these insights to the fabrication of various devices such as compact waveguide lasers with emission covering the near to the mid-infrared, as well as 3 dimensional integrated photonic circuits for astronomical applications.

8876-4, Session 1

Influence of hydrogenation on electrical conduction in HGCDTE thin films on silicon

Stephen Fahey, EPIR Technologies, Inc. (United States) and Air Force Research Lab. (United States); Paul Boieriu, EPIR Technologies, Inc. (United States); Christian P. Morath, Dustin Guidry, Laura Treider, Air Force Research Lab. (United States); Ramana Bommena, Jun Zhao, Sivalingam Sivananthan, EPIR Technologies, Inc. (United States)

HgCdTe is the standard state of the art infrared detector material for space applications. It is known that such HgCdTe detector performance can be lower in the presence of bulk crystal defects and dangling bonds at surfaces or interfaces. Passivation of such bulk defects and surfaces can potentially improve detector performance by saturating dangling bonds in dislocation cores, and at surfaces. Indeed, results showing improvement of HgCdTe current-voltage characteristics after hydrogenation have been published. Here we use multiple-carrier fitting of Hall effect data, acquired at variable magnetic field strengths and sample temperatures, to investigate the physical influence of hydrogenation, as a passivation procedure, on HgCdTe crystalline thin films on Si(211) substrates. We observe the following: (1) evidence of multiple active electrical carriers in all samples, (2) evidence of 2-dimensional electrical conduction before and after hydrogenation, and (3) changes in carrier concentration and mobility induced by hydrogenation.

8876-5, Session 2

Ionizing radiation effects on high operating temperature, broadband visible/infrared HGCDTE photodetectors *(Invited Paper)*

Silviu Velicu, Ramana Bommena, EPIR Technologies, Inc. (United States); Vince M. Cowan, Christian P. Morath, Air Force Research Lab. (United States); Stephen Fahey, EPIR Technologies, Inc. (United States)

Systems that gather data in separate spectral bands can determine both absolute temperatures and unique signatures of objects in the field of view. By providing this new dimension of contrast, broadband multicolor detection enables advanced color-processing algorithms that improve sensitivity beyond that of narrower band single-color devices. We present here our progress on the development of high-performance, two-color focal plane arrays that allow the simultaneous detection of radiation in the visible and infrared bands. The first band cover the 400 nm to 4 ?m wavelength range and is based on standard double-layer planar heterostructures technology. The backside-illuminated array has the substrate removed to allow for visible detection. The second color covers the 4-11 ?m wavelength range and is based on an Auger-suppressed architecture. This architecture allow for dark currents similar to the ones observed in the first color (400 nm - 4 ?m). Our detector architecture is grown using Molecular Beam Epitaxy (MBE) technique. MBE is the method of choice for multiple-layer HgCdTe growth because it produces material of excellent quality and allows composition and doping control at the atomic level. Such quality and control is necessary for the fabrication of multicolor detectors since they require advanced bandgap engineering techniques. State of the art performances over the full wavelength range were demonstrated. We will report on the optical and electrical characteristics of the two-color broadband elements before and after they are subjected to 63 MeV protons producing a total ionizing dose of 100 kRads (Si).

8876-6, Session 2

Proton radiation effects on the photoluminescence of infrared INAS/INASSB superlattices *(Invited Paper)*

Elizabeth H. Steenbergen, Air Force Research Lab. (United States); Zhiyuan Lin, Arizona State Univ. (United States); Vincent M. Cowan, Jeremy A. Massengale, Air Force Research Lab. (United States); Yong-Hang Zhang, Arizona State Univ. (United States); Christian P. Morath, Air Force Research Lab. (United States)

Infrared detector arrays operating in space must be able to withstand defect-inducing proton radiation without performance degradation. Therefore, it is imperative that the proton-radiation hardness of infrared detector materials be investigated. Photoluminescence (PL) is sensitive to electrically-active defects in materials, and thus can be used to quantify the effects of proton-radiation-induced defects. The temperature-dependent and intensity-dependent PL of a set of InAs/InAsSb superlattices (SLs) is examined before and after 63-MeV-proton irradiation. Two different proton doses, 50 kRad(Si) and 100 kRad(Si), were applied to two different pieces of each SL. The low temperature (5 K) peak positions of the irradiated samples varied in energy by only 1% from the non-irradiated sample. The exponent of the power law fit of the integrated intensity versus the input intensity changed by less than 10% for the irradiated samples, indicating negligible change in the recombination mechanism and defect density after irradiation. These results suggest InAs/InAsSb SLs may be suitable for space infrared detector arrays.

8876-7, Session 2

Radiation tolerance of type-II strained layer superlattice based interband cascade MWIR detector *(Invited Paper)*

Vincent M. Cowan, Christian P. Morath, Air Force Research Lab. (United States); Stephen Myers, Nutan Gautam, Ctr. for High Technology Materials (United States); Sanjay Krishna, The Univ. of New Mexico (United States)

Infrared (IR) detectors operated in the space environment are required to have high performance while being subjected to a variety of radiation effects. Sources of radiation in space include the trapped particles in the Van Allen belts and transient events such as solar events and galactic cosmic rays. Mercury cadmium telluride (MCT)–based IR detectors are often used in space applications because they have high performance and are generally relatively tolerant of the space environment when passivated with CdTe; often, the readout-integrated circuit is far more susceptible to radiation effects than the detector materials themselves. However, inherent manufacturing issues with the growth of MCT have led to interest in alternative detector technologies including type-II strained-layer superlattice (T2SLS) infrared detectors employing interband cascade architectures. Much less is known about the radiation tolerance properties of these SLS-based detectors compared to MCT. Here, the effects of 63 MeV protons on variable area, single element, InAs/GaSb SLS detectors utilizing an interband cascade architecture are considered. The device employs a seven-stage cascade region, each stage containing a MWIR absorber, graded T2SLS transport region, and an interband tunneling region. When semiconductors devices are irradiated with protons with energies of 63 MeV the protons are capable of displacing atoms within their crystalline lattice. The radiation effects on these detectors are characterized by dark current and quantum efficiency as a function of total ionizing dose (TID) or, equivalently, the incident proton fluence.

8876-8, Session 2

Noise measurements of an interband cascade MWIR detector in a radiation environment

Laura Treider, Christian P. Morath, Vince M. Cowan, Air Force Research Lab. (United States); Sanjay Krishna, The Univ. of New Mexico (United States)

Infrared (IR) detectors operated in the space environment are required to have high performance, while being subjected to a variety of radiation effects. Sources of radiation in space include the trapped particles in the Van Allen belts and transient events such as solar events and galactic cosmic rays. Mercury cadmium telluride (MCT)–based IR detectors are often used in space applications due to high performance and their being relatively tolerant of the space environment when passivated with CdTe. However, inherent manufacturing issues with MCT growth has led to interest in alternative detector technologies including type-II strained-layer superlattice (T2SLS) infrared detectors employing interband cascade architectures. Much less is known about the radiation tolerance of these III-V based detectors compared to MCT. Here, the effects of 63 MeV protons on InAs/GaSb SLS detectors utilizing an interband cascade architecture are considered. In this report, measurements of the noise current spectral density pre and post irradiation with 63 MeV protons producing a total ionizing dose of 100 kRad (Si) of the mid-wave infrared cascade detectors are presented. Noise is measured using an isolated system incorporating a battery-powered transimpedance amplifier incorporating a dewar-mounted feedback resistor RF and source-follower MOSFET, both held at 77 K. This configuration confines high detector impedance interfacing issues to the dewar, minimizes Johnson noise due to the feedback resistor, and enhances bandwidth by reducing stray capacitance. Features of the detector's noise spectrums at different bias and temperatures are examined.

8876-101,

DE-STAR: A Planetary Defense and Exploration System

Philip Lubin, Univ. of California, Santa Barbara (United States); Gary B. Hughes, California Polytechnic State Univ., San Luis Obispo (United States); Johanna Bible, Jesse Bublitz, Joshua Arriola, Caio Motta, Univ. of California, Santa Barbara (United States)

We propose an orbital planetary defense system capable of heating the surface of potentially hazardous objects to the evaporation point as a futuristic but feasible approach to impact risk mitigation. We call the system DE-STAR for Directed Energy Solar Targeting of Asteroids and exploRation. DE-STAR is a modular phased array of lasers powered by the sun. Modular design allows for incremental development, test, and initial deployment, lowering cost, minimizing risk, and allowing for technological co-development, leading eventually to an orbiting structure that could be erected in stages. The main objective of DE-STAR would be to use the focused directed energy to raise the surface spot temperature to <3000K, allowing direct evaporation of all known substances. The same system will heat the surface of an asteroid and eject evaporated material, which would create a large reaction force to alter the asteroid's orbit. Our baseline system is a DE-STAR 4 (10-km-sized array) system, which allows for asteroid engagement starting beyond 1 AU with a spot temperature sufficient to evaporate all known materials. Such a system can directly evaporate up to 500-m diameter asteroids in one year. Smaller asteroids, such as DA-14, could be completely evaporated in a few hours and the recent Chelyabinsk asteroid in less than one hour. The same system will also produce a reaction thrust comparable to the Shuttle SRB on the asteroid due to mass ejection and thus allow for orbital diversion of even larger asteroids, beyond several km in diameter. Smaller systems are also extremely useful. For example, a DE-STAR 2 (100-m size array) would be capable of diverting volatile-laden objects 100 m in diameter by initiating engagement at ~0.01-0.5 AU. Smaller objects could be diverted on shorter notice. The phased array

configuration is capable of creating multiple beams, so a single DE-STAR of sufficient size could engage several threats simultaneously, such as a Shoemaker-Levy 9 scenario on Earth. An orbiting DE-STAR would also be capable a wide variety of other functions. Narrow bandwidth and precision beam control would aid narrow search and ephemeris refinement of objects identified with wide-field surveys. Propulsion of kinetic or nuclear tipped asteroid interceptors or other interplanetary spacecraft is possible using a “photon rail gun” mode from direct photon pressure on a spacecraft propelling a 100-kg craft to 1 AU in 3 days and a 10,000-kg craft to 1 AU in 30 days. A DE-STAR could also provide power to ion propulsion systems, providing both a means of acceleration on the outbound leg, and deceleration for orbit insertion by rotating the spacecraft and using mirrors to divert the DE-STAR beam into the ion generation cavity. Vaporization and de-orbiting of debris in Earth orbit could be accomplished with a DE-STAR 1 or 2 system. DE-STAR 3 and 4 arrays may allow standoff interrogation of asteroid composition by observing absorption lines in the blackbody spectrum of a vaporizing surface spot. There are a number of other applications as well, including SPS. Multi-function capability aids in justifying such a system.

8876-9, Session 3

Post-flight test results of seed laser module subjected to space exposure *(Invited Paper)*

Narasimha S. Prasad, NASA Langley Research Ctr. (United States)

In this paper, the results of performance testing of a laser diode module sent by NASA Langley Research Center on MISSE 7 mission will be discussed. The objective of the Materials International Space Station Experiment (MISSE) is to study the performance of novel materials when subjected to the synergistic effects of the harsh space environment for several months. MISSE missions provide an opportunity for developing space qualifiable materials. This laser module was a part of lidar component package on the MISSE 7 box that was transported to the international space station (ISS) via STS 129 and returned to the Earth via STS 134. The STS 129 mission was launched on Nov 16, 2009 and the MISSE 7 package was brought back to the earth via the STS 134 that landed on June 1, 2011. This package that was in space environment for more than one and a half year included fiber laser, solid-state laser gain materials, coherent receiver, and semiconductor laser diode. The post-flight testing of several MISSE 7 materials that were recently returned back after more than one year of exposure on the International Space Station (ISS) is underway. This paper will present the comparison of pre-flight and post-flight performance curves and discuss the effect of space exposure on the laser diode module.

8876-10, Session 3

Photonics on the mission to Mars *(Invited Paper)*

Michael D. Watson, NASA Marshall Space Flight Ctr. (United States)

Human missions to Mars present some unique challenges for photonics devices. These devices will have exposure to many different space environments. During assembly they will be exposed to the earth orbiting environment. Upon departure they will need to function through the Earth’s Van Allen Radiation Belt. While the general interplanetary environment is less challenging than the radiation belt, they will operate in this environment for 18 months, subject to sudden saturation from solar flares. These components must continue to function properly through these saturation events presenting quite a challenge to photonic components, both optical and electronic. At Mars, the orbital environment is more benign than the Earth’s. Components used as part of the landing vehicles must also deal with the pervasive dust environment for 3 – 6 months. These assembly and mission execution environments provide every form of space environmental challenges to photonic components. This paper will briefly discuss each environment and the expectations on the components for successful operation over the life of the mission.

8876-11, Session 3

Fiber laser systems for space lasercom and remote sensing *(Invited Paper)*

Shantanu Gupta, Fibertek, Inc. (United States)

Space based laser remote-sensing for Earth observation or planetary atmospheres has traditionally relied on the mature component technologies of diode-pumped solid-state lasers and nonlinear frequency conversion. We highlight a few representative examples, including ongoing space mission programs at Fibertek: ICESat-2 and Cloud Aerosol Transmitter for ISS platform. Key design issues are highlighted, as well as the lessons learned from a multi-disciplinary design process and space-qualification requirements.

Fiber laser/amplifier systems coupled with the use of high-performance single-photon detectors provides a waveform-agile platform for various space based laser applications, such as space lasercom, space-based Earth (or planetary) remote sensing, and space-based imaging. In particular we discuss ongoing efforts at Fibertek on a space-qualifiable, high-performance multi-rate pulse-position modulated 1.5-um Er-doped fiber laser transmitter, for inter-planetary lasercom. Design, performance and qualification issues are discussed, along with recent results on its performance characteristics and ongoing qualification. In addition, high-speed electronics design and related qualification issues are also highlighted. As an example of a waveform-agile laser platform, adaptation of above hardware platform for space based sensing of atmospheric CO2 is also highlighted. As another parallel example, we also compare it to ongoing work on the development of 1-um Yb-fiber laser transmitters for space application.

8876-12, Session 3

A low-power and high-precision miniaturized digital sun sensor

Bart M. de Boer, Murat Durkut, TNO (Netherlands)

At TNO, a prototype of a low-power and high-precision miniaturized digital sun sensor (miniDSS) was developed, which is expected to be launched on QuadSat mid 2013 for in-orbit demonstration. The miniDSS provides a cost-effective, miniaturized an low-power alternative to conventional sun sensors, while maintaining comparably high accuracy.

The 5x5 mm2 application-specific integrated circuit (ASIC), which forms the core of the sun sensor, comprises a 2D active pixel array, read-out circuitry, the sun centroid algorithm and input/output functionality.

The sensor was optimized for low power consumption and consumes only 65 mW. This is roughly a factor 15 lower than found in conventional high-precision digital sun sensors. At dimensions of 69x52x14 mm3 and a weight of only 72 grams, the miniDSS has achieved an extreme reduction in both volume and weight as compared to conventional devices, i.e. roughly a factor 10 and 5, respectively.

Although the miniDSS is a miniaturized low-power device, the performance is state-of-the-art. The resolution is better than 0.007°, the noise equivalent angle was found to be 0.01° (3?) and the uncalibrated accuracy is, in the order of a few hundreds of a degree, across the field of view (FOV) of 102°x102°. Using correction based on ground calibration data, the residual errors can most likely be even further reduced.

In this presentation the innovative architectural design will be discussed, as well as the results of performance tests conducted in our laboratory sun simulator set-up. Finally, an outlook to future developments will be presented.

8876-13, Session 4

Interband cascade lasers: rapidly maturing mid-infrared sources *(Invited Paper)*

Chul Soo Kim, Joshua Abell, William W. Bewley, Charles D. Merritt, Chadwick L. Canedy, Igor Vurgaftman, Jerry R. Meyer, U.S. Naval Research Lab. (United States); Mijin Kim, Sotera Defense Solutions (United States)

Interband cascade lasers (ICLs) with maximum cw operating temperatures as high as 118ºC are extremely promising sources for the 3-6 um spectral range. This talk will review the current status of midwave infrared ICLs, along with future directions for improving their performance. One of the ICL's defining characteristics is its very low threshold drive power required to operate at ambient temperature, with values as low as 29 mW by comparison to nearly 1 W for state-of-the-art quantum cascade lasers (QCLs) emitting in the same spectral region. Approximately 200 mW of cw output power has been generated into a nearly-diffraction-limited output beam at room temperature, and the brightness was further improved by broadening the ridge and incorporating corrugations into the ridge sidewalls to suppress multimode lasing. In this manner, nearly 300 mW of cw output power was produced with M2 = 2.2. Short-cavity (0.5-mm-long) devices fabricated from the same wafer achieved a room-temperature wall-plug efficiency of nearly 15%, which approaches the QCL record. We have also demonstrated distributed-feedback (DFB) ICLs with single-spectral-mode emission at 3.7-3.8 um. One DFB ridge provided single-mode emission from 20ºC to 75ºC, with a maximum tuning range of 21.5 nm at the fixed current of 130 mA. The maximum current-tuning range at fixed temperature was 10 nm at 60ºC. The side-mode suppression ratio was estimated to exceed 30 dB. The maximum single-mode output for a device with HR/anti-reflection (AR) coatings was 27 mW at 40ºC.

8876-14, Session 4

Quantum cascade lasers for aerospace applications *(Invited Paper)*

Igor Trofimov, AKELA Laser Corp. (United States)

After almost two decades since their first demonstration, Quantum Cascade lasers (QCLs) have come of age. High-power continuous wave, as well as narrow linewidth DFB QCLs operating at room temperature are now available over the 4-12?m wavelength region. They have not only demonstrated multi-Watt output power, but also achieved high wall plug efficiency (WPE > 20% at room temperature). QCLs are thus poised to replace currently used laser sources such as CO and CO2 lasers and optical parametric oscillators (OPO) in many applications, and made all but obsolete lead salt diode lasers in mid-IR spectroscopy. The advances in QCLs have opened a wide realm of opportunities for applications of these lasers in defense and security, particularly in the air and space-borne systems.

This paper reviews the advances in QCL technology and its military and civilian applications including environmental monitoring, detection of chemical and biological warfare, infrared countermeasures, etc. It will also discuss issues of QCL reliability that are pertinent to aerospace missions.

8876-15, Session 4

Thermospectral properties of photonic crystal microcavity lasers and applications to systems with local temperature variations *(Invited Paper)*

Nathan J. Dawson, Michael Aviles, James H. Andrews, Michael Crescimanno, Joshua B. Petrus, Anthony Mazzocco, Youngstown State Univ. (United States); Kenneth D. Singer, Eric Baer, Hyunmin Song, Case Western Reserve Univ. (United States)

Microcavity lasers are well suited for future optical devices for space-based applications. They are paper thin and can be made of lightweight materials. Furthermore, melt-process co-extrusion methods can fabricate large sheets of low-cost, all-polymer, microcavity lasers with a variety of materials. Photo-chemically stable doped polymers have been shown to resist damage from solar radiation. The thermal properties of polymers, however, can alter the emission characteristics in these environments that exhibit large temperature fluctuations. Thus, by studying how temperature affects these polymer structures, a temperature stable and radiation resistant, all-polymer, microcavity laser may be designed with the potential to be a low-cost and lightweight optical device for harsh environments.

We report on the thermal properties that affect the emission wavelength during laser operation and some combinations of materials used in co-extruded Bragg reflectors. Two types of microcavity laser configurations are studied; (1) A Distributed Bragg Reflector (DBR) laser with a dye-doped gain medium enclosed by two Bragg reflectors of alternating polymer layers, and (2) a defect Distributed FeedBack (DFB) laser with a doubled center layer that reduces the threshold and increases the slope efficiency of a standard DFB laser. The defect DFB laser and the reflectors on the DBR laser are modeled using transfer matrix theory to observe shifts in the defect location and the reflection band edges that are induced by temperature changes. We use these results to predict stability criteria for future laser materials for space and other harsh environments.

8876-16, Session 5

DE-STAR: Phased-array laser technology for planetary defense, spacecraft propulsion, and other vital tasks *(Keynote Presentation)*

Gary Hughes, California Polytechnic State Univ., San Luis Obispo (United States); Philip Lubin, Johanna Bible, Jesse Bublitz, Joshua Arriola, Caio Motta, Univ. of California, Santa Barbara (United States)

We propose an orbital planet defense system to evaporate or divert potentially hazardous asteroids as a futuristic but possible method of alleviating impact risk. Called DE-STAR (Directed Energy Solar Targeting of Asteroids and exploRation), the system is a solar-powered, planar, modular array of high-power, phase-locked lasers in a synthetic aperture optical arrangement. Surface temperature needed to ablate most solid materials is >3000K, dictating a flux >5MW/m2. Ongoing surface vaporization beginning at 1AU allows sufficient time to evaporate objects approaching 1km diameter, or deflect larger objects. A phased array of side length ~10km produces ~70GW of laser power with ~30m spot size at 1AU, and delivers more than the required flux on target. With 50% sunlight-to-laser conversion efficiency (3x current technology), the required power is produced with a solar array of the same size. Smaller array stages would be capable of vaporizing surface materials at closer distances; reaction to ejected material generates significant force for deflecting an asteroid's orbit. An orbiting DE-STAR could also be used for many other critical tasks. Debris in Earth's orbit could be disintegrated or de-orbited. Interrogation of asteroid composition may be possible by observing blackbody spectra of the heated spot: absorption of characteristic radiation by materials in the evaporation plume could allow chemical analysis. Directing the DE-STAR beam at interplanetary spacecraft delivers significant accelerating force: a 1,000kg spacecraft could travel ~1AU to Mars in <15days. DE-STAR could also be used to decelerate the spacecraft for orbital insertion by envisioning an orbital vehicle that detaches from a larger transport and receiving energy reflected from the transport.

8876-17, Session 6

Superluminal ring laser gyroscopes and accelerometers for hypersensitive and compact inertial measurement units *(Invited Paper)*

Selim M. Shahriar, Joshua Yablon, Zifan Zhou, Ye Wang, Shih Tseng, Northwestern Univ. (United States)

When a ring laser is augmented by a medium that induces anomalous dispersion, the group velocity becomes much larger than the vacuum velocity of light, without violating causality of special relativity, thus producing the so-called superluminal ring laser. We have shown the the sensitivity of frequency shift as a function of cavity length change is enhanced by as much as six orders of magnitude in such a laser. This property can be exploited to realize ultra-sensitive gyroscope and accelerometers, which in turn can be combined to realize a superluminal inertial measurement (SIMU) unit that can outperform the state-of-the art, large scale IMUs while being very compact. An SIMU of this type is of significant interest for many applications under GPS denied conditions. In this talk, we will present details of our efforts towards realizing an SIMU using diode pumped alkali lasers augmented by a cell that induces Raman depletion in the gain profile.

8876-18, Session 6

Compact fiber optic gyroscopes for platform stabilization *(Invited Paper)*

Dave Pechner, William Dickson, James Coward, Andrew McClaren, SA Photonics (United States)

SA Photonics has developed a family of compact Fiber Optic Gyroscopes (FOGs) for platform stabilization applications. The use of short fiber coils enables the high update rates required for stabilization applications but presents challenges to maintain high performance. We are able to match the performance of much larger FOGs by utilizing several innovative technologies.

These technologies include source noise reduction to minimize Angular Random Walk (ARW), advanced digital signal processing that minimizes bias drift at high update rates, and advanced passive thermal packaging that minimizes temperature induced bias drift while not significantly affecting size, weight, or power. In addition, SA Photonics has developed unique distributed FOG packaging technologies allowing the FOG electronics & photonics to be packaged remotely from the sensor head or independent axis heads to minimize size, weight, and power at the sensing location(s). The use of these technologies has resulted in high performance, including ARW less than 0.001 deg/rt-hr and bias drift less than 0.004 deg/hr at an update rate of 10 kHz, and total packaged volume less than 30 cu. in. for a 6 degree of freedom FOG-based IMU.

Specific applications include optical beam stabilization for LIDAR and LADAR, beam stabilization for long-range free-space optical communication, Optical Inertial Reference Units for HEL stabilization, and Ka band antenna pedestal pointing and stabilization. The high performance of our FOGs also enables their use in traditional navigation and positioning applications.

This presentation will review the technologies enabling our high-performance compact FOGs, and will provide performance test results.

8876-19, Session 7

Femtosecond fiber laser based metal and semiconductor blackening and colorizing *(Invited Paper)*

Huan Huang, Lih-Mei Yang, Jian Liu, PolarOnyx, Inc. (United States)

No Abstract Available

8876-20, Session 7

High-power fiber-based laser development for space remote sensors *(Invited Paper)*

Fabio Di Teodoro, The Aerospace Corp. (United States)

Nanosecond(ns)-pulse fiber lasers (PFLs) offer important advantages for field applications over competing bulk solid-state lasers, primarily in terms of pulse format flexibility, efficiency, size and weight, and thermal management.

Recently, very large-core fibers such as photonic crystal fibers (PCFs) have also attained pulse energies, peak powers, and spatial/spectral brightness directly applicable to space-based remote sensors.

In this presentation, we will review the development of innovative ns PFLs having form factor and performance amenable to space deployment. The laser sources discussed will include an actively triggered master-oscillator/power-amplifier (MOPA) driven by a gain-switched, actively pulse-controlled, single-frequency diode laser and incorporating a multi-stage, 975nm-diode-pumped ytterbium(Yb)-doped, single-polarization fiber-based amplifier will be presented. The amplifier terminal stage consists of an Yb-doped segmented, 100um-core, rod-type PCF. The MOPA produced ~1064nm-wavelength, ~1.5ns pulses of energy/peak power in excess of 2.2mJ/1.5MW at pulse repetition frequency = 10 kHz, while exhibiting good beam quality (< 1.2 ? diffraction limit) as well as excellent pulse contrast, spectral brightness (>92% pulse energy within a 0.2nm window), and net electro-optic efficiency ~15%. This optical source was packaged via assembly techniques traceable to optical telecommunications components, within an enclosure of ~0.5ft3 (< 18 liters) volume designed for tolerance of field-level shock, vibration, and thermal profiles.

An outlook to further power scaling and ruggedization of PFLs for space payloads will conclude the presentation.

8876-21, Session 7

Generation of tunable laser sidebands near 2.05um for CO2 sensing application *(Invited Paper)*

Jihong Geng, AdValue Photonics, Inc. (United States); Yingxin Bai, Jirong Yu, NASA Langley Research Ctr. (United States); Shibin Jiang, AdValue Photonics, Inc. (United States)

Greenhouse gas (such as CO2) profiling/monitoring in the Earth's atmosphere is important for better understanding global climate evolution. For this application, high-energy single-frequency pulsed laser transmitters are required at both on-line and off-line wavelengths for use in air-borne/space-born lidar platforms. These high-power pulsed laser transmitters can be generated by injection-seeding technique, which requires multiple single-frequency laser lines. Furthermore, these frequency lines need to be offset-locked each other, and also locked to a specific molecular absorption line as well, which is a challenge if they are provided by multiple seed laser sources. In this talk, we will present our latest development of such a kind of multiple-line single-frequency laser source for the application. A single-frequency 2.05um fiber laser emits a monochromatic electromagnetic wave at a carrier frequency near

150THz. With a sinusoidal intensity modulation at a microwave frequency (several GHz), new laser frequency components (i.e., modulation side bands) can be readily generated, which offer a way to generate multiple well-defined single-frequency laser lines with a frequency spacing precisely controlled by a microwave signal generator. Spectroscopic application with the multiple-line single-frequency laser source will be discussed.

8876-22, Session 7

Improved nanofabrication for plasmonic nanostructures on optical-fiber tip for biosensors *(Invited Paper)*

Yongbin Lin, Robert G. Lindquist, The Univ. of Alabama in Huntsville (United States)

The capability of creating plasmonic nanostructures on the optical fiber tip with conventional nano-fabrication technologies would enable the transition of localized surface plasmon resonance (LSPR) based label-free biosensing technology from laboratory environment to field and space applications. The use of optical fiber platform for LSPR biosensing enables highly integrated and portable solutions for space life exploratory missions related to immunoassays and DNA hybridization assays. Multiple detections can be integrated into a single fiber bundle for multiple parallel analyses. Moreover, this fiber probe is very suitable for remote sensing in space applications where savings in reagents are very valuable. In this report we present an approach to create arrays of metallic nanoantennas on the end facets of optical fiber utilizing planar substrate nanofabrication technologies such as electron beam lithography and lift-off processes. We also show that post annealing of Au nanoantennas can reduce line width of the resonance spectra of Au nanodots array on optical fiber tip. Compared to commercial surface plasmon resonance (SPR) sensing systems (Biacore AB), our proposed device offers several advantages, including (1) it can be inserted into the fluids and specimens for insitu chemical and biological detection, (2) the fiber device can be used as a SERS probe, a function not found in conventional SPR detection systems, and (3) it allows remote sensing naturally. The fabrication methods allow rapid and inexpensive prototypes of nanostructures on optical fiber tip. Highly specific and sensitive detection of human interleukin-6 (IL-6) protein using this fiber-optic label-free biosensor will be presented.

8876-38, Session PMon

Photonic directed energy planetary defense and relativistic propulsion

Johanna Bible, Univ. of California, Santa Barbara (United States)

We propose a directed energy orbital planetary defense system capable of heating the surface of potentially hazardous objects to the evaporation point as a futuristic but feasible approach to impact risk mitigation. The system is based on recent advances in high efficiency photonic systems. We call the system DE-STAR for Directed Energy Solar Targeting of Asteroids and exploRation. DE-STAR is a modular phased array of solid-state lasers, powered by photovoltaic conversion of sunlight. The system is scalable and completely modular so that sub elements can be built and tested as the technology matures. The sub elements can be immediately utilized for testing as well as other applications including space debris mitigation. The ultimate objective of DE-STAR would be to begin direct asteroid vaporization and orbital modification starting at distances beyond 1 AU. Using the phased array to focused the beam the surface spot temperature on the asteroid can be raised to more than 3000K, allowing evaporation of all known substances. Further use of the DE-STAR could be propulsion of kinetic or nuclear tipped asteroid interceptors or other interplanetary spacecraft. A photon drive is possible using direct photon pressure on a spacecraft similar to a solar sail. Given a laser power of 50GW, A 100 kg craft can be propelled to 1AU in approximately 3.5 days achieving a speed of 0.4% the speed of light and a 10,000 kg craft in approximately 35 days.

8876-23, Session 8

Contamination protective coatings: an overview *(Invited Paper)*

Ronald G. Pirich, Independent Consultant and Senior Research Advisor (United States)

Dust, ice, fogging and corrosive contamination is a serious problem for air and space equipment and vehicles. For example, contamination may accumulate on sensors inhibiting accurate and timely data acquisition. Sensors that require transparency to light for maximum efficiency can be seriously affected by contamination buildup. The thermal and radiation environment of space systems also pose unique challenges to protective coatings because of the space environment's large temperature variations, the plasma environment and solar UV and X-rays induced photoemission of electrons. For polymeric materials, not all properties are affected to the same degree by radiation but are often localized at a specific bond. At the nano-scale, van der Waals forces can be significant. In general, these intermolecular forces are not affected by ionizing radiation unless the surface molecular structure is changed since van der Waals interactions are always present between molecules and only dependent on the number of electrons in the molecule and the distance between molecules. Both hydrophilic and hydrophobic coating approaches may be important to address specific design requirements. Hydrophilic materials are composed of polar molecules and have been used to defog glass and enable oil spots to be swept away with water. Hydrophobic molecules tend to be non-polar and thus prefer other neutral molecules and nonpolar solvents. Hydrophobic molecules often cluster and are difficult to wet with liquids. This paper presents an overview of various types of contamination that adheres to critical air and space surfaces and potential coatings phenomenology that may be used to eliminate contamination.

8876-24, Session 8

Simulation framework for space environment ground test fidelity *(Invited Paper)*

Jason A. Cline, Spectral Sciences, Inc. (United States)

The space environment produces a number of performance challenges to satellite and spacecraft manufacturers that require measurements, including effects from hyperthermal atomic oxygen, charged particles, magnetic fields, spacecraft charging, ultraviolet radiation, micrometeoroids, and cryogenic temperatures. Because of the significant resources involved in fielding spacecraft, ground testing against these effects is desirable.

Physics-based models can help test consumers knowledgably interpret the responses of the spacecraft and the uncertainties in the measurements. Ground-based tests are accelerated, the stimuli are sometimes approximate. Breakdown of approximations and synergies between effects can lead to nonlinear results, which without appropriate calibration or model-based guidance can cause inaccurate test readings. For example, Cline et al. (J. Spacecraft, 42(5):810, 2005) showed that accelerated atomic-oxygen tests can produce multicollision effects that decrease the average surface-impact energy of the atomic oxygen fluence. Although individual space effects models exist, we are not aware of a comprehensive model for space effects or for test chambers.

We present initial progress to fill this gap with an extensible multiphysics model network. The model network is designed to adapt to different levels of understanding and/or approximations, including several levels of physics from fundamental rates and parameters to space and test chamber simulations. The starting point for the effort is a rarefied gas dynamics model for atomic oxygen exposures. We present the status of the model, the roadmap for its development, data needs, and likely validation pathways.

8876-25, Session 8

Simulation of a pulsed atomic oxygen beam *(Invited Paper)*

Neal J. Carron, Rock West Solutions, Inc. (United States); Iain Boyd, Univ. of Michigan (United States); Scott M. Frasier, Aravant Corp. (United States); Matt Thomas, ATK Corp. (United States)

The Air Force has recently built a vacuum chamber for simulating the LEO space environment for testing small satellites or satellite subsystems. Seven environmental sources are provided: solar light flux; SC charging; outgassing; and individual beams of electrons, protons, Atomic Oxygen, and Xe ion backflux. In our talk we will present results of our recent computer simulation of the pulsed Atomic Oxygen source. We motivate our choice of the dynamical DSMC code used, and present results such as the AO fluence time history and its spatial distribution over the test article; chamber pressure time history; flow velocity contours; and the importance of particle-particle collisions; and attempts to model the motion of residual source-produced O+ ions in the geomagnetic field. We compare with existing measurements.

8876-26, Session 8

Modeling proton and heavy ion induced effects in thin film coatings for lunar and space environments

Edward W. Taylor, International Photonics Consultants, Inc. (United States); Ronald G. Pirich, Independent Consultant and Senior Research Advisor (United States)

Protective thin film coatings are important for many near-Earth and interplanetary space systems applications such as photonic components, optical elements, solar cells and detector-sensor front surfaces to name but a few environmentally at-risk technologies. The near-Earth and natural space environment consists of known degradation processes induced within these technologies brought about by atomic oxygen, micrometeorites, space debris and dust, solar generated charged particles, Van Allen belt trapped particles and galactic cosmic rays. The paper will focus on presenting the results of an investigation based on simulated ion-induced defect-modeling and nuclear irradiation testing of several innovative hybrid-polymeric self-cleaning coatings that appear to be suitable for many space photonic, lunar surface and avionic applications. Data is reported regarding the radiation resistance of several hybrid polymer coatings for protecting sensors, structures, and space vehicles from dust contamination and space radiation found in space and on the Moon's surface.

8876-27, Session 9

Fluorinated PPV type block co-polymers for nanophotonics *(Invited Paper)*

Sam-Shajing Sun, Thuong Nguyen, Jaleesa Brooks, Norfolk State Univ. (United States)

Polymer based optoelectronic materials and thin film devices exhibit great potential in space applications due to their flexibility, lighter weight, larger light absorption coefficient, and very promising radiation tolerance in space environment as compared to their inorganic semiconductor counterparts. Current existing polymer photovoltaic materials and devices suffer low photoelectric power conversion efficiencies due to a number factors including poor morphologies at nano scale that hinder the charge separation and transport, and poor electronic orbital match between the donor and the acceptor units and the solar spectrum. Due to carbon-fluorine (C-F) chemical bonds are much stronger than the typical carbon-hydrogen (C-H) bonds, fluorinated polymers are very attractive for outer space applications. This paper summarizes our recent work on a fluorinated DBA type block copolymer system where the donor (D) block contains a donor substituted and hydrocarbon based polyphenylenevinylene (PPV), and acceptor (A) block contains a fluorinated and acceptor substituted polyphenylenevinylene (f-PPV). Preliminary results reveal f-DBA exhibiting more efficient photoluminescence quenching (relevant to photo induced electron transfer between the donor and the acceptor blocks) and better nano phase morphologies as compared to D/A blend and the non-fluorinated DBA. The chemical synthesis, characterizations, and preliminary morphological/optoelectronic studies and results will be presented.

8876-28, Session 9

Quantum dots with built-in charge to increase responsivity, detectivity, and operating temperature of quantum dot infrared photodetectors *(Invited Paper)*

Andrei Sergeev, Victor Pogrebnyak, Univ. at Buffalo (United States); Alex Varghese, Michael Yakimov, Vadim E. Tokranov, Serge Oktyabrsky, Univ. at Albany (United States); Guillaume Thomain, Nizami Vagidov, Vladimir Mitin, Univ. at Buffalo (United States)

Quantum well infrared photodetectors are widely used in multi-elements focal plane arrays operating at liquid nitrogen temperatures. Compared to quantum-well structures, quantum dot (QD) nanomaterials are more flexible to control photoelectron processes by engineering of the nanoscale potential profiles formed by charged quantum dots. Quantum dots with built-in charge (Q-BIC) suppress capture of photoelectrons by (QDs) and provide strong coupling to infrared radiation. We review design approaches, fabrication and characterization of photodetectors based on Q-BIC media with strong selective doping to increase the dot charge. Characterization of Q-BIC media includes the structural, spectral (photoluminescence measurements) and electrical characterization (dark current, I-V measurements). After several design-growth-characterization cycles we reached relatively high density of quantum dots, small concentration of defects related to quantum dot growth, and suppressed carrier capture by QDs. Optimized Q-BIC media were used for fabrication of Q-BIC IR photodetectors. We studied spectral and temperature dependences of photoresponse and also its dependences on bias voltage and parameters of Q-BIC medium. Due to enhanced coupling to IR radiation and long photoelectron lifetime we demonstrated room temperature operation of our detectors and reached responsivity of ~10^3 A/W. In our devices the dark current increases with dot's charge approximately in the same way as the responsivity. Because the detector sensitivity is proportional to the responsivity and inversely proportional to the fluctuation current, which in turn is proportional just to the square root of the dark current, the sensitivity improves with charging of quantum dots. Currently the room-temperature detectivity of ~10^8 cm?Hz1/2/W is obtained.

8876-29, Session 9

Radiation effects on solar cells: experiments, models, and simulations: DLTS vs SRIM for trap data *(Invited Paper)*

Alexandre I. Fedoseyev, Marek Turowski, Timothy Bald, Ashok Raman, CFD Research Corp. (United States); Jeffrey Warner, U.S. Naval Research Lab. (United States)

A predictive computational approach that limits use of DLTS experiments is presented, developed using the experimental data and proposed physics based models. Three-dimensional NanoTCAD simulations are used for physics-based prediction of space radiation effects in III-V solar cells, and validated with experimentally measured characteristics of a p+n GaAs solar cell with AlGaAs window. The computed dark and illuminated I-V curves as well as corresponding performance parameters matched very well experimental data for 2 MeV proton irradiation at various fluences. We analyze the role of majority vs. minority and deep vs. shallow carrier traps in the solar cell performance degradation. The traps/defects parameters used in the simulations were derived from Deep Level Transient Spectroscopy (DLTS) data obtained at NRL. It was noticed that the degradation caused by deep traps observed in single-trap numerical tests exhibit a very similar trend to the degradation caused by a full spectrum of defect traps, but to a lesser degree. This led to the development of a method to accurately simulate the degradation of a solar cell by using only a single deep level defect whose density is calculated by the Stopping and Range of Ions in Matter (SRIM) code. Using SRIM, we calculated the number of vacancies produced by 2 MeV proton irradiation for fluences ranging from 6x1010 cm-2 to 5x1012 cm-2. Based on the SRIM results, we applied trap models in NanoTCAD and performed full I-V simulations from which the amount of degradation of performance parameters (I¬sc, Voc, Pmax) was calculated. The physics-based models using SRIM allowed obtaining good match with experimental data.

8876-30, Session 10

Germanium on silicon to enable integrated photonic circuits *(Invited Paper)*

F. Kenneth Hopkins, Air Force Research Lab. (United States); Kevin M. Walsh, Univ. of Louisville (United States)

Although Integrated Photonic Circuits (IPCs) including the optical analog-to-digital converter and the integrated optical spectrum analyzer were first explored during the mid-1970's, the impact of IPCs on DoD and commercial systems has been limited. The need for integrated photonic circuits has been highlighted again in recent DoD program announcements. Requirements for IPC's in general include a common substrate, for which silicon has recognized advantages, and the use of laser wavelengths near1.55µm in order to utilize commercially available ultra-narrow line laser diodes and optical filters. Although many integratable subcomponents have become available during recent decades, an ideal photodiode is conspicuously absent. Silicon photodiodes, although easily integratable, are intrinsically slow (<~1GHz) and not responsive to 1.55µm light. GaInAs photodiodes are fast, well developed, and highly responsive to 1.55µm light but have limited potential for true integration with silicon and optical waveguides. In contrast, germanium photodiodes promise high responsivity with the added benefit of true integration. Within the past year, Duan and others confirmed the high responsivity of Ge photodetectors by demonstrating a photodetector (a Ge detector region and a Si avalanche region) with an enormous responsivity of 12A/W and a high frequency response (8 GHz). [Optics Express 20 (7May2012), 11031] In the presentation, the results of our study of the potential for integrating Ge photodetectors into IPCs will be described. Our efforts entail the deposition of high quality germanium films on silicon to fabricate Ge-based photodiode structures for detecting light in fiber or in optical slab waveguides.

8876-31, Session 10

Recent progress of Spectrolab high-efficiency space solar cells *(Invited Paper)*

Daniel C. Law, Spectrolab, Inc. (United States)

Multijunction space solar cell technology has achieved production cells with average 1-sun efficiency close to 30% with cell sizes ranging from, 26.6 to 74.4-cm2. The latest XTJ SuperCells are built in Spectrolab newly established 150-mm manufacturing line. Inverted metamorphic (IMM) 3- and 4-junction cells with a target average 1-sun efficiency of 33% are being developed. 4-cm2 and 24-cm2 IMM4J cells exceeded 34% and 32% efficiency respectively. The IMM cells were assembled into strings and affixed to rigid aluminum honeycomb panel for thermal cycling characterization. Preliminary temperature cycle data of the IMM cell strings showed no degradation. Semiconductor bonded technology (SBT), an alternative approach that can achieve efficiency ≥35% will also be presented.

8876-32, Session 10

Detection advantages of spatial oversampling in imaging sensors *(Invited Paper)*

Jerry A. Wilson, John T. Caulfield, Cyan Systems (United States); Nibir K. Dhar, Defense Advanced Research Projects Agency (United States)

Cyan Systems has recently developed an approach to focal plane assembly (FPA) architecture which represent a significant advancement in information extraction from the data as it is being collected. This approach utilizes sub-pixels which achieve a high degree of oversampling of the sensors Point Spread Function (PSF), well beyond the Nyquist limit. The data contained in an oversampled image has the obvious advantage of readily discriminating between focal plane and object generated artifacts as the first step in false alarm rejection. However there are further advantages that can be exploited through nearest neighbor subpixel correlation, thresholding and pooling that achieves significant noise reduction and therefore improved sensitivity. In Cyan's architecture these processes are accomplished for the first time at the input to the preamp in the ROIC. This approach not only allows improved fidelity in imaging, but further reduces false alarm rates, improves detection ranges, and demonstrates an improved ability to track closely spaced objects. The architecture has been modeled and simulations run which illustrate the dramatic improvements possible.

8876-33, Session 10

A highly strained INAS/GASB type II superlattice for LWIR detection *(Invited Paper)*

Yiqiao Chen, SVT Associates, Inc. (United States)

IR photo detectors are in high demand for various military and civilian applications, such as airborne surveillance, remote sensing, environmental monitoring, and spectrometry. Recently InAs/GaSb type II superlattice (T2SL) has attracted numerous R&D interest since SLS is the only IR material that has a theoretical prediction of higher performance than HgCdTe. Here we report the improvement of SL photo diodes through a novel design with highly-strained type-II superlattice (HS-T2SL). The HS-T2SL consists of a highly compressively strained thick InSb layer at InAs/GaSb interfaces. The overall net strain in HS-T2SL remains zero as a result of strain compensation, thus avoiding strain-induced defects during growth. At a localized level the strain in HS-T2SL causes tetragonal distortions in k-space which shift the bulk energy levels and split the valence band degeneracy of the light- and heavy-hole energy levels. The presence of coherent strain shifts the band edges such that the SL energy gap is reduced. This reduced band gap is advantageous to photodetectors because longer cut-off wavelengths can be obtained with reduced layer thickness in the strained SL. The highly compressive strain in HS-T2SL also leads to an even higher optical absorption coefficient and lower dark current. Applying this new design resistance-area product (R0A) is measured as high as 2.1 Ohm-cm2 at 85K for 14.5um-cutoff photo diodes without any dark current suppression barriers. The fabricated 14.5um-cutoff photo diode shows Johnson-noise-limited peak detectivity of 8.4?10^10 cmHz1/2/W at zero bias at 85K.

8876-34, Session 11

Quantum interference in electro-optic polymeric modulators *(Invited Paper)*

Javier Perez-Moreno, Skidmore College (United States) and Washington State Univ. (United States)

The performance of polymer-based electro-optic modulator is very dependent on the wavelength of operation of the device. Surprisingly, most of our intuitive understanding of the molecular performance in such devised are based on studies performed in the off-resonance regime, where the nonlinear optical response of the molecule is by assumption not dependent on the wavelength of operation; or/and two-level model extrapolation, where the response is assumed to be dominated by the contribution of only one excited state. In either case, the effects of quantum interference (cancellation and enhancement of the response due to interactions between multiple excited states) are ignored. In this paper we show how in complex molecules with more than one excited state, quantum interference effects plays an important role in determining the on-resonant response, and hence should not be ignored when studying the response of organic-based electro-optic materials.

8876-35, Session 11

Pulse electro-acoustic (PEA) measurements of embedded charge distributions *(Invited Paper)*

J. R. Dennison, Utah State Univ. (United States); Lee H. Pearson, Box Elder Innovations (United States)

Knowledge of the spatial distribution and evolution of embedded charge in thin dielectric materials has important applications in semiconductor, high-power electronic device, and high-voltage DC power cable insulation industries. In space environments, spacecraft are exposed to extreme charged particle fluxes ranging from relatively low (<100eV) to high (>100keV) energies. Charge can accumulate in dielectric materials, until potentials are high enough to initiate electrostatic discharge (ESD). Such events can damage electronic components in the spacecraft and lead to system failures. Knowledge of how, where, and how much charge accumulates and how it redistributes and dissipates for given materials, spacecraft configurations and space environments is the key to prediction, avoidance and mitigation of these destructive “arc and spark” spacecraft charging effects.

High-frequency pulsed-electro-acoustic (PEA) and Pressure Wave Propagation (PWP) measurements are non-destructive methods used to investigate such internal charge distributions. PEA techniques generate acoustic waves within the material by using high-voltage, high-frequency pulsed signals to stimulate motion of the internal charge bound in the solid, then measures the ensuing voltage pulse response. We discuss the instrumentation, methods, theory and signal processing of simple PEA experiments and shows results of PEA measurements. We emphasize system improvements required to achieve high spatial resolution for in vacuo measurements of thin film polymeric, ceramic, or glass dielectric materials using medium to high energy (~103eV to ~107eV) electron beams.

*Work is supported by Phase I and II STTR projects sponsored by the Air Force Research Laboratory (AFRL).

8876-36, Session 11

Deterministic digital WDM LAN for controlled configurations *(Invited Paper)*

John Mazurowski, The Pennsylvania State Univ. Electro-Optics Ctr. (United States)

We present a small digital Local Area Network (LAN) using Wavelength Division Multiplexing (WDM), meant for deterministic applications with fixed or controlled configurations. For these special cases, efficiency can be increased, and acquisition cost decreased. This network uses time, wavelength, and spatial domains to provide determinism and to increase efficiency.

For wavelength efficiency, the network uses a Lambda-Net architecture, where each receiver is dedicated to a specific wavelength. To reach a receiver, a transmitter must transmit at the receiver wavelength.

Transmitters are either dedicated or tuned to a desired wavelength. Typical of communication transmitters in the 1550 nanometer band, controlled cooling is required to maintain wavelength accuracy. To increase cooling efficiency, a bank of transmitter diodes shares a micro-environment with common cooling.

Each transmitter is pre-modulated with a clock; the frequency of the clock depends on the application and the required timing resolution. For low frequency applications, a switch can be used in lieu of a modulator to keep or discard clock pulses, providing a data stream.

To avoid undesired phase modulation, and to provide for timing respective to the network geometry, we have the choice of adding chromatic dispersion or adding incremental delay to each wavelength channel.

All network nodes are transparent. The data plane can be merged with the control plane to accommodate high bandwidth payloads. Within a node, an external signal can replace a section of clock or control signal as a payload. After the payload is transmitted, clock or switched clock signals resume.

8876-37, Session 11

Fiber optic strain, temperature and shape sensing via OFDR for ground, air and space applications *(Invited Paper)*

Joseph J. Bos, Mark E. Froggatt, Eric Sanborn, Justin Klein, Dawn Gifford, Luna Innovations Inc. (United States)

Optical fiber sensors provide numerous advantages for space, air and ground applications. They are small, light-weight, immune to EMI, radiation resistant, and can be embedded in a material or adhered to its surface. In this work, recent advancements in OFDR-based optical fiber temperature, strain and shape sensing are demonstrated.

Utilizing Rayleigh backscatter (RBS) from off-the-shelf single mode fiber as the transducer, OFDR technology enables low-cost, fully-distributed sensing with mm spatial resolution and high dynamic range. Potential applications for this technology include design verification, testing and in-situ structural health monitoring (SHM) of ground, air and space vehicles, satellite structures and subcomponents. Presented here are dynamic, fully-distributed thermal measurements of a thermal-barrier coated metal structure as it is exposed to a high-temperature torch. The thermal field on the surface is mapped in high resolution and coating defects are detected and located.

Advancements in OFDR-based shape sensing systems enable real-time 3D shape, position, bend and twist measurements with unprecedented spatial resolution and positional accuracy. Potential applications for this technology include SHM, coordinate measurements, and real-time feedback for shape-enhanced deformable structures such as flexible antennae, imaging optics and their supporting structures, solar sails and more. Presented in this work are real-time position, shape and twist measurements of a simple structure as it is subjected to various loads.

8877-18, Session PMon

The impact of space-time speckle to the resolution in range and azimuth direction on synthetic aperture imaging ladar

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Synthetic aperture laser ladar is theoretically the most possible optical method to provide centimeter-class resolution with a real aperture size of a few meters in thousand kilometers. However, as linear chirp laser signal is always employed as the transmitted signal, SAIL is inevitably impacted by the space-time varying speckle effect. In many SAIL two-dimensional reconstructed images, the laser speckle effect severely reduces the image quality. We have indicated that the random phase and random amplitude introduced by space-time speckle is closely related to the ratio of the scale of antenna aperture and the average width of speckle pattern. In this paper, expressions for two-dimensional data collection contained space-time speckle effect are obtained, and the influence of space-time speckle effect to the resolution element imaging is analyzed. According to computer simulation results, the width of the resolution in range direction almost keeps the same, while the peak value of the range resolution decreases when the speckle random phase variance increases. The random phases introduced by Fourier transform in range direction have little influence on the azimuth imaging. After matched filtering, the resolution in azimuth direction is degraded severely by the speckle random phase, even divided into more than one points.

8877-20, Session PMon

Optical imaging process based on two dimensional Fourier transform for synthetic aperture imaging ladar

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The synthetic aperture imaging ladar systems typically generate large amounts of data difficult to compress with digital method. This paper presents an optical SAIL processor based on compensation of quadratic phase of echo in azimuth direction and two dimensional Fourier transform. The optical processor mainly consists of one phase-only liquid crystal spatial modulator(LCSLM) to load the phase data of target echo and one cylindrical lens to compensate the quadratic phase and one spherical lens to fulfill the task of two dimensional Fourier transform. We give detailed description of principle and mathematical analysis of this optical processor and analyze the difference of imaging processing result between complex data and pure phase data. We show the imaging processing result of practical target echo obtained by a synthetic aperture imaging ladar demonstrator. The preferable result indicates the effectiveness of this optical SAIL processor. Due to the inherent parallel and the speed-of-light computing capability of this optical processor, both the time and power demanding to compress SAIL target echo are reduced comparing to the digital processing way. The optical processor is compact and lightweight. It has a promising application future especially in onboard and satellite borne SAIL systems.

8877-21, Session PMon

A transformation approach for aberration-mode coefficients of Walsh functions and Zernike polynomials

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The power series expansion or function basis expansion is the common way of describing wavefront distortion. At present, the Zernike-polynomial representation has been widely adopted and regarded as the classic and the standard because the polynomials form a complete and orthogonal set and the low-order polynomials have the same distribution with actual aberrations in optical systems. However, the coefficients of the high-order Zernike polynomials cannot be directly measured using common wavefront sensing techniques. Besides, in theory, any complete and orthogonal function series can be used as basis to represent wavefronts. As a result, the binary complete and orthogonal Walsh functions have been modified and utilized as binary-aberration-mode basis by some novel wavefront sensing techniques. These functions have only two values, -1 and 1, so they are especially suitable for representing discrete wavefront. But when wavefront sensing techniques based on binary-aberration-mode detection trying to reconstruct common wavefronts with continuous forms, the Modified Walsh functions are incompetent. The limited space resolution of Modified Walsh functions will leave substantial residual wavefronts. In order to sidestep the space-resolution problem of binary-aberration modes, it's necessary to transform the Modified-Walsh-function expansion coefficients of wavefronts to the Zernike-polynomial coefficients and use Zernike polynomials to represent the wavefronts to be reconstructed. For this reason, a transformation method for wavefront expansion coefficients of the two aberration modes is proposed. The principle of the transformation is the linear of wavefront expansion and the method of least squares. Through expanding each Zernike polynomials with the Modified Walsh functions, the aberration-mode-coefficient transformation matrix is built. The Zernike-polynomials coefficients of a wavefront can be calculated with the matrix and the Modified-Walsh-functions coefficients acquired. The numerical simulation demonstrates that the transformation with the matrix is reliable and accurate.

8877-1, Session 1

Multi-conjugate adaptive optics: capabilities and limitations versus technological demonstration and scientific productivity

Katharine J. Jones, WBAO Consultant Group (United States)

From 1995 to 2000, the first astronomical science results were obtained using Rayleigh scattering by the Starfire Optical Range. The first use of sodium guide stars was obtained at the Calar Alto telescope in 2000. Astronomical LGS was again used in 2004 using the 3 m Lick telescope. The first large telescope was the 10 m Keck II in 2005. The first LGS AO papers from 8 m Gemini - North and VLT appear in 2008. The LGS AO with the Suburu telescope began in 2008.This paper will address ground-based Adaptive Optics Multi-Conjugate observatories requiring compensation for extended aberration. Of particular interest is science productivity. The following observatories will be examinded and compared: Keck I and Keck II, Gemini Nortth and Gemini South, LBT (Large Binocular Telescope) and VLT (Very Large Telescope). Gemini North, Keck I & II and VLT are single conjugate AO. Gemini South is multiple conjugate. LBT is ground layer AO. Science performance is a function of laser return and the number of subapertures.The number of refereed papers is an indictor of science productivity

8877-2, Session 1

Phased beam projection from tiled apertures in the presence of turbulence and thermal blooming

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The individual phases of a multi-beamlet laser source can be manipulated by exploiting high-bandwidth phase loops to correct for aberrations induced within the optical beamlet trains. With the current state of the art in phasing technology, this phasing of the beamlet trains is successfully accomplished up to a common aperture sharing element or on a point-source target; however, in the presence of an extended target, rough surface scattering through laser-target interaction adds the additional constraints of speckle and depolarizing effects. In particular, speckle phenomena and atmospheric effects create unobservable modes in the beam control system. One such unobservable mode is termed stair mode and is appropriately identified by a stair-step pattern of piston phase across the individual subapertures that comprise a tiled aperture. This paper investigates the effects of turbulence and thermal blooming on phased beam projection from tiled apertures using wave-optics simulations. To represent different array fill factors in the source plane, both seven and 19 element hexagonal close-packed tiled apertures are used in the simulations along with both Gaussian and flat-top outgoing beamlets. Peak Strehl ratio and power in the bucket are calculated in the target plane over multiple random realizations that are then averaged. This is done for all simulation setups with and without the presence of stair mode.

8877-3, Session 1

Image-based wavefront compensation using deformable mirror for remote sensing telescope

Norihide Miyamura, Meisei Univ. (Japan)

We are developing an adaptive optics system for earth observing remote sensing sensor. In this system, high spatial resolution has to be achieved by a lightweight sensor system due to the launcher's requirements. Moreover, simple hardware architecture have to be selected to achieve high reliability. Image based AOS realize these requirements without wavefront sensor. In remote sensing, it is difficult to use a reference point source unless the satellite controls its attitude toward a star or it has a reference point source in itself. We propose the control algorithm of the deformable mirror on the basis of the extended scene instead of the point source. In our AOS, a cost function is defined using acquired images on the basis of the contrast in spatial or Fourier domain. The cost function is optimized varying the input signal of each actuator of the deformable mirror. In our system, the deformable mirror has 140 actuators. We use basis functions to reduce the number of the input parameters to realize real-time control. We constructed the AOS for laboratory test, and proved that the modulated wavefront by DM almost consists with the ideal one by directly measured using a Shack-Hartmann wavefront sensor as a reference.

8877-4, Session 1

Aero-optic analysis of turbulent boundary layer by direct integration method

Chien-Pin Chen, The Univ. of Alabama in Huntsville (United States); John Price, The Univ. of Alabama in Huntsville (United States); George W. Sutton, John E. Pond, Analysis and Applications Associates (United States)

We have investigated the direct integration of the Helmholtz equation for the aero-optical effects of a turbulent boundary layer on a flat plate for a 10-cm aperture. The turbulence of the boundary layer was found by using a hybrid Large Eddy Simulation (LES) -Reynolds averaged Navier-Stokes (RANS) method. The turbulence fields are shown to compare favorably with experimental results. The hybrid methods allowed for the study of the optical models and also validation of their assumptions. The far-field intensity of a uniformly illuminated circular aperture in vacuum was used to validate our direct integration method. It is well established that a turbulent boundary layer has packets of elongated structures with a preferred angular orientation downstream. Thus, aero-optic aberrations should show an anisotropic behavior as a function of propagation angle. We demonstrated this effect, as the downstream-direction propagation through elongated structure results in greater aberration, versus propagation in the upstream direction. The Optical Path Difference, (OPD), was computed and found to compare favorably with experimental data. The OPD was also used for the direct integration of the Helmholtz equation to find the point spread function, (PSF), at various propagation angles. Correlation lengths and variances of the index-of-refraction fluctuations distribution, along the line-of-sight were also calculated. The point spread function was then computed using the assumption that the turbulence in the boundary layer is isotropic and homogeneous. The errors made using these assumptions were found by comparing these results to the direct integration method that uses the OPD from the LES simulation.

8877-5, Session 1

Sodium guide star excitation and preferable laser formats

Katharine J. Jones, WBAO Consultant Group (United States)

Sodium guide stars are in a variety of types. Power, laser type, pulse and spectral format have been tabulated. High output power is not enough. The physics of coupling light to the sodium atom can affect how much of this power is returned as signal to the AO system. Laser beam quantity and launch beam diameter can drastically affect AO system performance. For laser sodium interaction, there are 29 energy levels, 8 ground states and 16 excited states. The transition from the P2a line yielding lambda = 589 nm is the one important for the Laser Guide Star. With proper laser intensity, the atom can be excited once per relaxation line (~16 ns) giving the largest apparent cross section: the most photon return per unit incident light. Some effects can spoil ideal pump conditions. Quenching can be corrected by repumping. Addressing more Doppler bins with lines at least 110 MHz plus the laser line width should be done to mitigate deleterious effects. Some laser spectral formats wii be explored and compared for improved atomic coupling for brighter guide star per unit laser output.

8877-6, Session 1

Sequential diversity imaging: experimental correction of dynamic aberrations

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Phase diversity has proven to be a viable technique for wavefront sensing but converges too slowly for real-time applications. Sequential diversity imaging (SDI) is a variation on phase diversity that we have implemented on a laboratory testbed, which includes a surface parallel actuated deformable mirror (SPA-DM) and a high frame rate imager in the optical path. The SPA-DM applies small corrections to the wavefront at each frame update. These dithers produce the phase diversities and the sequential images that are the measurement set for the phase diversity algorithm. By taking advantage of the small frame-to-frame wavefront changes in a closed-loop system, convergence within a frame period can be obtained. Our testbed was designed to explore the performance of

the SDI technique under dynamic aberrations. We present experimental results with improved imagery and report on the conditions where the technique is useful. Typically the frame-to-frame OPDs must be reasonably small (< 0.3 waves) and the DM dithering must be much faster than the disturbance (~ 10X). The practicality of performing the SDI calculations at the speeds of interest for atmospheric compensation is discussed.

8877-7, Session 2

Multi-shot compressed coded aperture imaging (MCCAI)

Xiaopeng Shao, Tengfei Wu, Changmei Gong, Xidian Univ. (China); Hong Chang, Weihai Vocational College (China)

The classical methods of compressed coded aperture(CCA) still require an optical sensor with high resolution, although the sampling rate has broken the Nyquist sampling rate already. A novel architecture of multi-shot compressed coded aperture imaging(MCCAI) using a low resolution optical sensor is proposed, which is mainly based on the 4-f imaging system, combining with two spatial light modulators(SLM) to achieve the compressive imaging goal. The first SLM employed for random convolution is placed at the frequency spectrum plane of the 4-f imaging system, while the second SLM worked as a selecting filter is positioned in front of the optical sensor. By altering the random coded pattern of the second SLM and sampling, a couple of observations can be obtained by a low resolution optical sensor easily, and these observations will be combined mathematically and used to reconstruct the high resolution image. That is to say, MCCAI aims at realizing the super resolution imaging with multiple random samplings by using a low resolution optical sensor. To improve the computational imaging performance, total variation(TV) regularization is introduced into the super resolution reconstruction model to get rid of the artifacts, and alternating direction method of multipliers(ADM) is utilized to solve the optimal result efficiently. The results show that the MCCAI architecture is suitable for super resolution computational imaging using a much lower resolution optical sensor than traditional CCA imaging methods by capturing multiple frame images.

8877-8, Session 2

Investigation results of high-resolution designs for large-scale diffractive coded aperture imaging sensors

Abraham Shrekenhamer, American Systems Corp. (United States); Stephen R. Gottesman, Northrop Grumman Electronic Systems (United States)

An investigation into the feasibility of achieving high-resolution imagery using Coded-Apertures Imaging (CAI) at wavelengths where diffraction effects are significant has yielded a set of design rules for Coded Aperture (CA) mask patterns, cell sizes and mask sizing which are substantially different from the traditional CAI designs presently employed for x-ray and gamma-ray imaging. A key finding in our work is the realization that when operating at longer wavelengths where diffraction becomes a significant factor, the radiance on the focal plane is dominated by speckle patterns which reduce the effectiveness of the traditional image retrieval techniques employing the mask pattern itself for correlation. Image retrieval from diffractive patterns requires a set of reference speckle patterns pre-calculated for point sources. Ultimately the diffractive sensor resolution is defined by the mean speckle size which can be minimized by reducing mask cell size while increasing overall mask dimensions. This implies that large-scale imaging sensors are required to produce high resolution images. We report the results of a comprehensive investigation into the relationship between wavelength, CA cell, mask sizing, and mask pattern type using Large-Scale CAI Simulation tools developed in the previous year. The result is a set of design guidelines researchers can now adapt for the design of high-resolution CAI sensors.

8877-9, Session 2

Estimation of illuminator scintillation in laser-illuminated imagery

David C. Dayton, Applied Technology Associates (United States)

It is well known that atmospheric turbulence corrupts the phase front of laser beam propagation. The phase distortions manifest themselves as intensity fluctuations when the beam is propagated over some distance. This intensity fluctuation is often referred to as scintillation. Laser illuminated imaging systems are used for a variety of applications including night time imaging and tracking. The illuminator intensity fluctuation is often considered a noise effect on the imagery, however if an estimate of the scintillation can be separated from the images, it would be useful in estimating atmospheric turbulence parameters. In past work we have used a Bayesian estimation approach to separate the illuminator fluctuations from the target images. In this paper we extend that approach to included calculations of the spatial and temporal statistics of the scintillation estimate to extract atmospheric turbulence parameters.

8877-10, Session 2

Inverse synthetic aperture ladar: a high-fidelity modeling and simulation tool

Casey Pellizzari, Air Force Research Lab. (United States); Mark Spencer, Air Force Institute of Technology (United States); Nicholas Steinhoff, John Belsher, Glenn A. Tyler, the Optical Sciences Company (tOSC) (United States); Skip Williams, Stacie Williams, Air Force Institute of Technology (United States)

A wave-optics model is developed which allows simulation of an Inverse Synthetic Aperture LADAR (ISAL) imaging system. This end-to-end tool models the complex interactions of Linear Frequency Modulated (LFM) chirped pulses, target/beam interactions including target articulation, speckle phenomenology, heterodyne detection with noise, atmospheric turbulence, and laser-guide star adaptive optics. Detected signal outputs are simulated and processed to explore system design trades and to test and compare image processing algorithms. Model verification results will be presented as well as reconstructed images.

8877-11, Session 3

Optimum pattern of the multi-aperture receiver for the synthetic aperture laser imaging ladar in the turbulence environment

Jianfeng Sun, Yu Zhou, Ya'nan Zhi, Liren Liu, Shanghai Institute of Optics and Fine Mechanics (China)

Synthetic aperture laser imaging ladar's optical receiver is a heterodyne detect system, so the atmosphere turbulence will affect the phase history of the ladar seriously. Unlike in conventional passive optical imaging system, both the wavefront distortion and piston term will decrease the imaging resolution. The distortion of the wavefrom decreases the heterodyne mixing efficient; the piston will cause the pulse-to-pulse phase errors. Multi-aperture receiver technology can improve the heterodyne mixing efficient efficiently, but the pattern of multi-aperture should be optimized according to different turbulence intensity. In this paper, we optimize a four-aperture receiver pattern in different turbulence environment. The simulation and experiment results are obtain in our ladar system.

8877-12, Session 3

An adaptive total variation image reconstruction method for speckles through disordered media

Changmei Gong, Xiaopeng Shao, Tengfei Wu, Xidian Univ. (China)

Multiple scattering of light in highly disordered medium can break the diffraction limit of conventional optical system. As the propagation properties of light through scattering media can be represented by transmission matrix (TM), once the transmission matrix is measured, the target image can be reconstructed from its speckle image through the disordered media. However, the reconstruction image obtained by common image reconstruction algorithms such as projection method and Tikhonov regularization approach has a rather low signal-to-noise ratio (SNR) due to the experimental noise and reconstruction noise, greatly reducing the quality of the result image. The above two noises can be effectively suppressed by adaptive total variation (TV) image reconstruction method. In this paper, we generate the transmission matrix of a turbid media, and simulate the speckle image formed by the multiple scattering of a test image through the turbid media since the element of transmission matrix of scattering media follows circular Gaussian distribution. Subsequently, a new regularization term corresponding to the statistics characteristic of TM is introduced into adaptive TV image reconstruction model to suppress the noise of restored image further. Numerical simulation experimental results show that the new image reconstruction method can greatly damped the noise of the restored image and consequently boosts the SNR and the sharpness of the restored image.

8877-13, Session 3

L1-based variational methods for low-power surveillance

Matthew S. Keegan, Kang-Yu Ni, Shankar R. Rao, HRL Labs., LLC (United States)

We describe an application of l1- based variational methods to the processing of high-throughput, high-resolution video surveillance data. The goal is to facilitate the design of an efficient surveillance system that detects interesting targets and foregrounds without storing or manipulating massive video data.

For surveillance cameras with small controllable motions, the background scene can be considered stationary, and the foreground data can be considered sparse since they appear fleetingly in the spatiotemporal domain. Our approach first leverages methods for Sparse and Low-Rank Decomposition and Robust Alignment to extract significant and stationary background features while running online. We then apply a novel method that uses optimized projections based on the learned background to reduce the number of measurements necessary for retrieval of foreground objects from the video stream data via l1-based variational reconstruction. Finally, we propose the novel Contiguity-Constrained Compressive Sensing (CCCS) reconstruction framework -- a novel joint l1-TV reconstruction algorithm to isolate the pixel-wise contiguous foreground data. Optimization techniques using functional splitting are proposed to numerically compute the CCCS reconstruction.

The proposed methods allow the reduction of data bandwidth and storage, and can be implemented in optical hardware, such as the Rice single-pixel camera, to reduce the number of measurements captured at each frame. Reducing camera power consumption, these factors facilitate the design of low-power video surveillance systems. Results demonstrate that effective foreground detection can be maintained with as little as 20% of video data.

8877-14, Session 3

Context and task-aware knowledge-enhanced compressive imaging

Yuri Owechko, Shankar Rao, Kang-Yu Ni, HRL Labs., LLC (United States)

We describe a Compressive Optimal Foveated Architecture (COFA) for image analysis applications that utilizes knowledge of the task to be performed to reduce the number of required measurements compared to Nyquist sampling based approaches. COFA adapts the dictionary and compressive measurements to structure and sparsity in the signal, task, and scene by reducing measurement and dictionary mutual coherence and increasing sparsity using principles of Actionable Information and foveated compressive sensing. Actionable Information extracts task-relevant regions of interest (ROIs) from a low-resolution scene analysis by eliminating the effects of nuisances for occlusion and anomalous motion detection. From the extracted ROIs, preferential measurements are taken using foveation as part of the compressive sensing adaptation process.

The task-specific measurement matrix is optimized by using a novel saliency-weighted coherence minimization with respect to the learned signal dictionary. This incorporates the relative usage of the atoms in the dictionary. Therefore, the measurement matrix is not random, but based on the dictionary structure and atom distributions. We utilize a patch-based method to learn the signal priors. A tree-structured dictionary of image patches using KSVD is learned which can sparsely represent any given image patch.

We have implemented COFA in an end-to-end simulation of a vehicle fingerprinting task for aerial surveillance using foveated compressive measurements adapted to hierarchical ROIs consisting of background, roads, and vehicles. Our results show 113x reduction in measurements over conventional sensing and 28x reduction over compressive sensing using random measurements.

8877-15, Session 3

Comparison of forward models and phase retrieval for image formation from intensity interferometer data

Richard B. Holmes, Boeing LTS Inc. (United States); David R. Gerwe, Jean J. Dolne, The Boeing Co. (United States); Peter N. Crabtree, Air Force Research Lab. (United States)

Many imaging techniques provide measurements proportional to Fourier magnitudes of an object, from which one attempts to form an image. One such technique is intensity interferometry which measures the squared Fourier modulus. Intensity interferometry is a synthetic aperture approach that is known to obtain high resolution information, and is effectively insensitive to degradations from atmospheric turbulence. These benefits are offset by the intrinsically low signal-to-noise ratio (SNR) of the technique. Forward models have been theoretically shown to have best performance for many imaging approaches. On the other hand, phase retrieval is designed to reconstruct an image from Fourier-plane magnitudes and object-plane constraints. So it's natural to ask, "How well does phase retrieval perform compared to forward models in cases of interest?" Image reconstructions are presented for both techniques in the presence of significant noise. Preliminary conclusions are presented for attainable resolution versus SNR for unity Fourier magnitude

8877-16, Session 4

Incoherent image simulation approach with wave optics

Thomas A. Underwood, David G. Voelz, New Mexico State Univ. (United States)

An approach is presented for numerically simulating incoherent imaging using coherent wave optics propagation methods. The approach employs averaging of irradiance from uncorrelated coherent waves to produce incoherent results. Novel aspects of the method include 1) the exploitation of a spatial windowing feature in the wave optics numerical propagator to play the role of an absorbing boundary and 2) a simple propagation scaling concept to avoid aliased field components after the focusing element. Classical linear systems theory is commonly used to simulate incoherent imaging when it is possible to incorporate aberrations and/or propagation medium characteristics into an optical transfer function (OTF). However, the technique presented here is useful for investigating situations such as “instantaneous” short-exposure imaging through distributed turbulence and phenomena like anisoplanatism that are not easily modeled with the typical linear systems theory. The relationships between simulation variables such as spatial sampling, source and aperture support, intermediate focal plane, etc., are discussed and the requirement or benefits of choosing these in certain ways are demonstrated.

8877-17, Session 4

Cramer-Rao bounds for variance of Fourier magnitude measurements

Richard B. Holmes, Boeing LTS Inc. (United States); David R. Gerwe, Jean J. Dolne, The Boeing Co. (United States); Brandoch Calef, Boeing LTS Inc. (United States); Peter N. Crabtree, Air Force Research Lab. (United States)

Many imaging modalities measure Fourier components of an object, from which one attempts to form an image. Given such data, reconstruction of an image from noisy and sparse data is especially challenging, as may occur in some forms of Fourier telescopy, intensity interferometry, and speckle imaging. Such Fourier magnitudes, or squared magnitudes in the case of intensity interferometry, must be positive, and moreover must be less than 1 given common normalizations of u-v plane data. Does this additional information provide significant value? Such information can be viewed as either a constraint or a form of prior information. The Cramer-Rao formalism is applied to single Fourier magnitude measurements to ascertain whether a reduction in variance is possible. Results are presented in dimensionless form, based on the Cramer-Rao bound on variance, and compared to maximum-likelihood results for variance and root-mean-square (RMS) error. It is found that application of constraints can significantly reduce variance but that biases are introduced that can increase the RMS error. The Cramer-Rao formalism is also extended to address the value of relatively general prior information, and results are presented for this extended formalism.

8877-19, Session 4

The influence of lenslet number on superresolution reconstruction for TOMBO imagery

Yuan Gao, Ping Yang, Bing Xu, Institute of Optics and Electronics (China)

Thin observation module by bounded optics (TOMBO) is an optical system that achieves compactness and thinness by substituting a micro lens-let array with smaller apertures for a conventional large full aperture. This array allows us to capture multiple low resolution sub-images of the same scene and use them to reconstruct a high resolution image. For one TOMBO system, the number of CCD pixel is usually fixed. The larger lens-let number is, the fewer pixels every sub-image has. For super-resolution algorithms, performance bounds exist. Moreover, resolution improvement quickly becomes marginal when increasing the number of sub-images. Therefore, finding a lens-let number to optimize super-resolution reconstruction for TOMBO imagery becomes an important practical problem.

Our approach simulates image capture process of TOMBO imagery under different lens-let number condition. The degradation processes of input images are decomposed into blurring, global translation, down sampling and adding noise. Then a multi-image super-resolution algorithm based on the maximum a posteriori (MAP) framework is applied for reconstructing high resolution images with sub-images from different lens-let number condition respectively. At last Mean Square Error (MSE), Peak Signal to Noise Ratio (PSNR) and Mutual Information (MI) of super-resolution images are calculated for image quality assessment. With statistical analysis, influence results from hundreds of synthetic and real images as input images are presented. Curves of super-resolution image quality vs. lens-let number show the optimal lens-let number for TOMBO imagery.

8877-22, Session 4

Signal demodulation of Fourier telescopy based on spectrum correction

Yang Li, Bin Xiangli, Wenxi Zhang, Yunfeng Nie, Academy of Opto-Electronics (China)

Fourier telescopy(FT) is a computational imaging technique. Three or more beams from different spatially separated transmitters are pointed at a distant and faint object. The spatial Fourier spectrum of the object is carried on the reflected temporally modulated signals. The conventional demodulation processing is calculating spectrum directly by inverse Fourier transform. However spectrum estimated by inverse Fourier transform has non-negligible errors caused by frequency shift error of the Acousto-optical modulator, the noise and the motion of the target. An improved demodulation method based on spectrum correction of FT is proposed. The method corrects the amplitude and the phase on the demodulated frequency of the signal by which better reconstructed image can be obtained. On the FT applied to fast-moving targets, the exact velocity of the distant target is hard to know. The developed demodulation method is also necessary to be hired to correct the frequency shift error. In this paper, we analyze the effect of the frequency shift error on Fourier telescopy demodulation. The degradation of the reconstructed image is simulated. We summarize the new demodulation method based on spectrum correction and give the simulated comparison between the conventional demodulation and the new method. A FT laboratory experiment result is also given to demonstrate the feasibility of the method.