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10098-1, Session 1

Ultra-low threshold supercontinuum generation in SnS-based clusters *(Invited Paper)*

Nils Rosemann, Justus-Liebig-Univ. Giessen (Germany); Jens P. Eussner, Andreas Beyer, Stephan W. Koch, Kerstin Volz, Stefanie Dehnen, Philipps-Univ. Marburg (Germany); Sangam Chatterjee, Justus-Liebig-Univ. Giessen (Germany)

The development of supercontinuum sources is advancing fast in the last decades. As do all nonlinear effects, the supercontinuum generation strongly relies on the nonlinearity of the active material. This nonlinearity may be greatly enhanced in specially designed photonic-crystal fibers, making supercontinuum sources widely available. Nevertheless, pulsed lasers are required to supply high enough field strengths to overcome the threshold for supercontinuum generation.

We study a new cluster based class of nonlinear media that exhibits ultra-low thresholds for supercontinuum generations, thus enabling the use of a low coast steady-state laser diode as the driving laser [1].

The clusters are composed of a tin sulfide based core that is surrounded by four organic ligands. The core adopts an adamantane-like architecture, [Sn4S6]. It has a tetrahedral shape and thus lacks inversion symmetry, enabling nonlinear processes. The four ligands (R = 4-(CH2=CH)-C6H4) are consolidating the structure of the core. Yet, as they are randomly oriented around the Sn-C bonds, they are also preventing any long-range order in the solid phase of the compound. As a result, the compound is obtained as a white powder with totally frustrated order.

This powder has been studied in respect to its optical properties. When irradiated with a continuous-wave infrared laser of sufficient intensity it emits a warm white spectrum that is virtually independent from the pump-wavelength in a range of 725-1050 nm. Lowering the pump intensity, however, changes the spectral weight to the red, similar to dimming of thermal emitters. The input-output characteristics, however, exclude a thermal process as the source of the observed white-light. Additionally semi-classical calculations of the white-light generation process are performed, underlining this statement.

[1] Rosemann N.W., et al.; Science, 2016, 352, 1301-1304

10098-2, Session 1

Ultra-broadband III-nitride digital alloys active region for optoelectronic applications

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In recent decades, III-Nitride semiconductors have developed as the key material in high efficiency light-emitting diodes for solid-state lighting. The III-Nitride family (AlInGaN) provides an extremely large bandgap range (0.64 eV to 6 eV) which is attractive for other optoelectronic applications. Conventional III-Nitride quantum-well active regions produce relatively narrow optical transition spectra which limit their implementation to narrow spectral emission. This work is interested in developing novel methods to achieve broadband optical emission in III-Nitride semiconductors, for used in broadband device applications.

In this work, we propose a III-Nitride digital alloy (DA) nanostructure as a promising candidate for the broadband active region design. The III-Nitride DA comprises an ultra-short period superlattice that can be obtained by periodical epitaxial growth of different ultra-thin III-Nitride epilayers (for example AlN/GaN and InN/GaN) consisting of a thickness of several monolayers. Our studies show that the III-Nitride ultra-thin epilayers introduce strong inter-well resonant coupling within the DA structure producing superlattice minibands. With further reduction of the thickness of each III-Nitride epilayer, the inter-well resonant coupling becomes enhanced leading to broadened energy minibands. Meanwhile, a realistic III-Nitride DA with a finite number of periods results in a digitized miniband with finite confined states. Therefore, an III-Nitride DA with sufficient periods has enough confined states to densely fill the minibands, and eventually all possible interband transitions between these confined states result in the desired broadband optical transition spectrum. Our findings demonstrate the potential of applying III-Nitride DA as promising active region for broadband optoelectronic applications.

10098-3, Session 1

Temperature dependent photoluminescence studies of quaternary Ga(P,As,Bi) alloys

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Quaternary alloys based on gallium arsenide (GaAs) opened a wide field of investigations in the past decades. From all available combinations, dilute bismuth (Bi) containing alloys are promising candidates for active materials with band gaps in the infrared region. Besides the large band-gap reduction of about 80meV per percent of Bi, enhanced spin-orbit coupling increases the splitting between the valence bands in Bi containing III/V alloys [1]. The latter reduces fundamental loss processes like Auger recombination, ultimately resulting in an increased efficiency and temperature stability of devices based on this alloys [2]. Nevertheless, the large atomic radius of Bi results in a large lattice mismatch of Ga(AsBi) towards GaAs. The incorporation of phosphorus into Ga(As,Bi) helps to overcome this mismatch.

To investigate the influence of the Bi incorporation on the band-gap we study a series of low temperature grown Ga(P,As,Bi) epilayers on GaAs substrates by temperature-dependent photoluminescence (PL) spectroscopy.

The shift observed for different P and Bi compositions is in good agreement with the band-gap reduction predicted by theoretical calculations. Nevertheless, a double s-shape is observed for variations of the lattice temperature from 10 to 300K. This indicates that despite the good sample quality, there is a remaining degree of disorder found in the samples.

[1] Alberi K., et al.; Appl. Phys. Lett., 2007, 91, 51909

[2] Usman M., et al.; Phys. Rev. B., 2011, 84, 245202

10098-4, Session 1

Electron spin dynamics in GaAsBi quantum wells

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GaAs-based dilute bismide materials have been intensively studied this past decade due to the strong modification of the band structure induced by the introduction of bismuth atom in the GaAs matrix. Indeed, bismuth content increase leads to a fast reduction of the band gap energy, together with a large increase of the spin-orbit splitting energy. This behavior has lead to suggest the use of these highly-mismatched alloys in a wide range of applications from telecommunications and photovoltaics to spintronics. However, the large spin-orbit coupling in this material is responsible for fast electron spin relaxation mechanism. Here we have probed the electron spin dynamics by time and polarization-resolved photoluminescence on a series of quantum wells grown by molecular beam epitaxy. On one hand, we observe a strong reduction of the spin relaxation times when the bismuth fraction increases, as compared to GaAs quantum wells. This is consistent with Dyakonov-Perel spin relaxation mechanism for which efficiency increases as the conduction spin splitting increases. On the other hand, some samples have evidenced spin filtering effects, probably due to spin-dependent recombination processes, which leads to an efficient temporal bounce of the photoluminescence polarization . This latter feature is much slower than the initial spin relaxation time, and strongly dependent on the material quality though. We will hence discuss the potential of dilute bismide nanostructures for spintronic applications, taking into account the material quality and band structure as key parameters.

10098-5, Session 1

On the identification and understanding of limiting factors in IQE of GaN:Eu-based PIN diodes for red light emission

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The unique luminesce properties of Eu+3 ions incorporated in the GaN host has enabled the utilization of GaN:Eu as a red light emitter. More specifically, Eu+3 ions present in the host can be excited via capture and recombination of e-h pairs in nearby traps and form complexes. Electrically driven GaN:Eu based devices such as GaN P-I-N diodes with an undoped GaN:Eu layer (I layer) and GaN:Eu based quantum wells (QWs) have been fabricated, demonstrating red luminescence under forward bias. Despite their low internal quantum efficiencies (IQE) of the two type of devices, GaN:Eu based QW exhibited superior characteristics over the GaN:Eu PIN diodes probably due to higher current injection efficiency (CIE) into the Eu+3 ions achieved by the carrier confinement into the GaN:Eu QW.

In this work we utilize the drift-diffusion theory in combination with the excitation mechanism of Eu+3 ions in order to develop a CIE model for the electrically driven GaN:Eu PIN diodes. Parameters associated with this excitation path such as capture rate from traps, transfer and back-transfer energy rate as well as dissociation rate of complexes are considered. In addition the CIE model of GaN:Eu PIN diode is compared with the CIE model for a GaN:Eu based QW. Our findings allowed the identification of the limiting factors of the efficiency of GaN:Eu PIN diodes. In addition, through the analysis of the CIE model the optimization of CIE in both type of devices is crucial for the enhancement of the efficiency of GaN:Eu based red light emitters.

10098-6, Session 2

Nanophotonic modulators and photodetectors using silicon photonic and plasmonic device concepts *(Invited Paper)*

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Nanophotonic modulators and photodetectors are key building blocks for high-speed optical interconnects in datacom and telecom networks. Besides power efficiency and high electro-optic bandwidth, ultra-compact footprint and scalable co-integration with electronic circuitry are indispensable for highly scalable communication systems. In this talk, we give an overview on our recent progress in exploring nanophotonic modulators and photodetectors that combine the specific strengths of silicon photonic and plasmonic device concepts with hybrid integration approaches. Our work comprises electro-optic modulators that exploit silicon-organic hybrid (SOH) and plasmonic-organic hybrid (POH) integration to enable unprecedented energy efficiency and transmission speed, as well as waveguide-based plasmonic internal photo-emission detectors (PIPED) with record-high sensitivities and bandwidths.

10098-7, Session 2

Modal dispersion of plasmonic coaxial nano-apertures for sorting angular momentum beams

Xiangping Li, Jinan Univ. (China); Boyuan Cai, Institute of Photonics Technology (China)

Owing to their exceptional optical properties, surface plasmons reveal the new perspective for tailoring light matter interaction at the sub-wavelength scale [1,2], which is of interest to a wide spectrum of scientists. In particular, optical properties of nanoscale apertures in metallic films have been intensely researched for their practical significance in nanophotonic devices such as color filters, near-field probes, nanolithography, optical data storage and so on [3-6]. The understanding of their modal dispersion behavior in these nano-apertures is of paramount importance, in turn, which offers new aspects for controlling their plasmonic properties for the subsequent applications.

Here we show that the modal dispersion behavior of plasmonic coaxial nano-apertures composed of a dielectric ring slit with thickness of d enclosed by a gold core with radius r1 and a gold cladding with radius r2, as schemed in the inset of Fig. 1a. The analytical solution of the guided modes in the plasmonic coaxial nano-apertures to Maxwell's equations can be expressed in cylindrical coordinates. The field distribution can be obtaind in terms of modified Bessel functions [7]. Fig. 1a shows the dispersion plot of guided modes supported in the coaxial nano-aperture with r1=200 nm and r2=225 nm. The guided modes with different angular momentum states are illustrated in Fig. 1b. As the frequency increases, the supported modes experience a gradual transition, so called cutoff, from the guided propagating (the real part of the propagation constant is significantly larger than the imaginary part) to the primarily leaky (the real part of the propagation constant is significantly smaller than the imaginary part). It reveals that as the angular momentum, specifically higher-order mode, increases the cutoff frequency of these modes grows. In addition, it exhibits

that the maximal supported higher-order mode is dependent on the radius of the coaxial nano-apertures. When the r1 is reduced to 75 nm, only the higher-order mode with mode index of 1 can be supported. This feature can be employed to selectively transmit beams carrying different angular momentum states, providing that the coupling to the guided mode is most efficient when the incoming plasmonic wave carries the identical angular momentum [8].

10098-8, Session 2

Estimation of power coupled into multi-moded surface plasmon waveguides: effect of power non-orthogonality of modes

Shivani Sital, Univ. of Delhi South Campus (India); Enakshi Khular Sharma, University of Delhi South Campus (India)

Over the recent years, surface plasmon waveguides have been extensively studied to realize sub-wavelength confinement in photonic nano-circuits. An array of periodic nanoscale holes on a thin metal sheet has been found to exhibit extraordinary transmission properties. These arrays can be considered as an array of a few-moded surface plasmon waveguides, often formed by coupling between nearest neighbor interactions. Hence, it is important to estimate the total power coupled into such plasmonic waveguides from a given incident field. The excitation coefficient for the individual modes supported by plasmonic waveguides can be evaluated by the use of their mode orthogonality. However, these lossy modes are not power orthogonal. Hence, for estimating the total power coupled into the waveguide one has to take into account the cross modal terms arising due to the fact that the modes are not power orthogonal. We have first illustrated the procedure by evaluation of the total coupled power in the excitation by a (Si) on silicon oxide (SiO_2) dielectric waveguide of the modes of a two moded multi-layer plasmonic waveguide configuration formed by loading the Si on SiO_2 waveguide with an air-gold-silicon-nitride (Si_3N_4) plasmonic waveguide. Such a configuration has been shown earlier to act as a TE pass polarizer with high extinction ratio in a very short spatial extent. Next the power coupled into of the nano-holes in a thin metal sheet by a plane wave has been considered in terms of excitation of the few mode plasmonic waveguides.

10098-9, Session 2

Evolutionary algorithms for radiative decay engineering of nanoplasmonic devices

Imran Hossain, Ahmet Cicek, Ahmet A. Yanik, Univ. of California, Santa Cruz (United States)

Lifetimes of the localized plasmonic excitations are inherently controlled by the type of the metals and the geometry of the nano-antennas. Most recently, radiative decay engineering approaches has taken significant attention in controlling the lifetimes of the plasmonic excitations and obtaining dramatically enhanced near-fields. However, these approaches require homogeneous dipolar couplings among nano-antennas. In practice, nano-antennas are fabricated at the interfaces of different materials with varying radiative phase velocities and interference conditions, a strong complication in designing the optical devices. To overcome these limitations, we invented an evolutionary algorithm solving the inverse problems starting from the desired optical resonance characteristics and finding the optimized device designs with strongly controlled radiative decay characteristics. Unlike conventional nanoplasmonic device design approaches based on trial-and-error, our evolutionary design algorithm allows efficient and rapid design of nanoplasmonic devices. Using our novel approach, we experimentally demonstrated high quality plasmonic resonances and dramatically enhanced near-fields that are well beyond what is achievable with conventional nano-antenna designs.

10098-84, Session 2

Voltage control of surface plasmon and phonon interactions in doped semiconductor-dielectric interfaces

Mohsen Janipour, Ibrahim Burc Misirlioglu, Kursat Sendur, Sabanci Univ. (Turkey)

At optical frequencies, the surface plasmon polaritons (SPPs) can be excited under special conditions due to the resonant coupling of the incident electromagnetic field and free electrons of the metal medium at the interface of a noble metal and a dielectric (DE) medium. The latter optical behavior strongly depends on plasmon frequency, which is a function of the density of free carriers in the metallic medium. At lower frequency bands, such as the terahertz regime, this phenomenon is more challenging to achieve with metals because of their perfect electrical conducting property in terahertz and lower frequencies. Thus the metal-dielectric interface structure may have challenges for far-infrared (IR) plasmonic applications. Several methods other than the classical metal-dielectric interfaces have been studied for exciting the SPPs at lower frequency bands such as invisible IR. In this paper we investigate the plasmon dispersion curve and show that the SPP excitation can be engineered through an external bias voltage using the inherent properties of the p-doped GaAs–dielectric interface. We also demonstrate that the origin of this behavior is due to the surface plasmon and phonon interactions at the metal-DE junction.

10098-10, Session 3

Experimental and theoretical investigation of convective Nozaki-Bekki holes in a Fourier domain mode-locked laser

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We investigate, both experimentally and theoretically, the appearance of convective structures in a Fourier Domain Mode-Locked (FDML) laser. Such laser consists of a long fiber ring unidirectional cavity which includes a semiconductor optical amplifier and a tunable narrow bandwidth optical band pass Fabry-Perot filter. The FDML regime refers to the case when the frequency of the filter transmission is driven in resonance with the cavity round trip frequency. In this case we observe the appearance of a stable frequency modulated solution. However, when there is a frequency mismatch between the filter modulation frequency and the cavity round trip frequency, the transitions between various frequency modulated solutions occur. In such a case, we observe the appearance of noise-induced structures that are similar to Nozaki-Bekki holes commonly observed in the 1-dimensional complex Ginzburg-Landau equation. These solutions that are continuously generated by the inherent noise of the laser, evolve in turbulent fronts that drift toward a wider turbulent regime. We theoretically describe this system using a set of coupled time delayed equations and show that these localised domains are associated with the presence of a sub-critical bifurcation. To further investigate such behaviour, we develop a numerical model that allows us for studying the creation, propagation and disappearance of these structures in the limit of an infinitely long cavity.

10098-11, Session 3

Optical bistability, self-pulsing and XY optimization in silicon micro-rings with active carrier removal

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We study the nonlinear dynamics of dispersion-engineered silicon ring cavities with active carrier removal. In this system, linear dispersion, Kerr nonlinearity, two-photon absorption (TPA), free-carrier dispersion / absorption (FCD / FCA), play a key role in the dynamics and steady-state behavior of the device [1]. Silicon rings are a good platform for studying these effects because the fabrication technology is relatively mature, leading to high intrinsic Q factors and good control over the ring dimensions. Moreover, devices can be fabricated inside a PN junction, so the carrier lifetime can be controlled by by active carrier removal.

By tuning the system parameters (pump power, carrier extraction, cavity detuning, ring dimensions), we can recover familiar nonlinear optical phenomena. For long carrier lifetimes, carrier effects dominate over the Kerr effect and the ring exhibits simple single-mode optical bistability, an important resource for photonic logic [2]. As the carrier lifetime is shortened, self-pulsing behavior is observed [3]; the resulting limit cycles can be used as an optical analog memory for neuromorphic applications [4] and Ising/XY optimization problems [5]. For short carrier lifetimes, the Kerr effect dominates and one can observe parametric amplification, frequency-comb generation and the formation of optical solitons [6].

The more exciting phenomena occur at the boundaries between these familiar regions. For example, if the dispersion and carrier lifetime are appropriately engineered, a system should exhibit both bistability and soliton formation, which is promising because the soliton peak-field enhancement should reduce the required average power for bistability. We also test synchronously-pumped designs, based on our previous work with chi(2) optical parametric oscillators [7].

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[2] H. Mabuchi, "Nonlinear interferometry approach to photonic sequential logic." Applied Physics Letters, 99(15):153103 (2011)

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10098-12, Session 3

Characteristics of ultrafast passively mode-locking soliton fiber laser utilizing higher-order mode fibers

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For a large range of enthralling applications in telecommunications, spectroscopy and material processing, soliton fiber lasers have been intensively explored as compact light sources of generating ultrashort pulses with stable peak power, owing to the balance between optical Kerr effect and cavity dispersion. Meanwhile, to fulfill the ever-increasing capacity demand for high-bit-rate fiber-optic communication systems, space-division multiplexing (SDM) technique has attracted much attention using multicore fibers or few-mode fibers (FMF). Nonetheless, to achieve high output energy in present ultrafast fiber lasers, key challenges include low repetition rate and possible pulse breaking due to excessive nonlinear phase accumulation. To resolve aforementioned issues, multiple-pulsing or bound solitons with discrete fixed pulse separations have been purposed in passively mode-locked fiber lasers, whereas random phase and inter-pulse interference would impair the system performance. In this work, we systematically investigate the formation and dynamics of synchronized soliton pulses in multiple spatial modes operating in large normal or anomalous dispersion by solving the complex cubic–quintic Ginzburg–Landau equation. For a mode-locked laser cavity design at 1565 nm with maximum output power of 150 mW utilizing FMF, whose large mode area can reduce nonlinearities caused by high-peak power intensities, the loop length of FMF laser cavity is 5-meter-long with 2000-ppm erbium-doped concentration. The FMF has a triple cladding index profile supporting four linearly polarized modes. Our results show that due to soliton fission by intermodal nonlinear coupling, energy is transferred from higher order modes to fundamental mode to stabilize mode-locking and realize high-repetition-rate fiber laser.

10098-13, Session 3

Coherent pulse progression in nonlinear quantum-cascade laser medium under group-velocity dispersion

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We present our theoretical analysis on coherent pulse progression in mid-infrared quantum-cascade lasers (QCLs) under group-velocity dispersion (GVD) and major intracavity nonlinearities including the background saturable absorber effect and the self-phase modulation (SPM). The study is carried out by numerically solving the Maxwell-Bloch formulism based on a two-level medium. The coherent effect is taken care of through the couplings among the electric field, polarization, and population inversion. To the best of our knowledge, the work carries the novelty of including both GVD and coherence in the study of pulse propagation in the QCL medium. We found that SPM and GVD have the cancellation effect in the time domain. In the frequency domain, they affect the spectrum in different aspects. The anomalous GVD effect excites the symmetric side modes around the central mode, with closer side-mode splitting under stronger GVD. This corresponds to the pulse duration extension in the time domain. The GVD does not affect the linewidth of each mode. The SPM effect broadens the linewidth of each mode, which is reflected as the pulse shortening in the time domain. But it does not change the spectral spacing between the central mode and the side mode. This study lays a foundation for our further pursuit of conditions for soliton propagation in the QCL medium by varying the dispersion and nonlinear properties of the lasing cavity. Our evaluation of GVD influence somewhat agrees with conclusions draw from the study of GVD effect on QCL frequency combs conducted by Faist's research group.

10098-14, Session 3

Fast-recovery of the amplitude and phase of mode-locked pulses using a frequency-swept source heterodyne measurement

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We present a heterodyne technique to recover the amplitude and phase of mode-locked pulses using a frequency-swept source. This technique builds on the stepped-heterodyne technique where the phase difference between consecutive mode-locked modes is obtained by beating these modes with a reference cw laser. By repeating this measurement for various wavelengths of the cw laser, one can obtain all the consecutive phase differences and recover the phase of each mode. By using a swept source, only one measurement is required to obtain the spectral amplitude and phase of periodic optical signals without having any prior spectral information of the signal under test. We use a linear swept source to scan the entire optical spectrum. These characteristics permit to cover all the spectral components of the periodic signal in a single continuous sweep. The signal under test is mixed with the output of the swept source while the beat signal is recorded on a fast oscilloscope. A spectral analysis is performed on the result signal with a short-time Fourier transform (STFT) allowing the recovery of instantaneous beat frequency that gives the exact frequency of each mode in addition to the repetition rate of the signal. We filter out the beat signal at every time corresponding to an instantaneous frequency lower than half the repetition rate. We can then recover simultaneously the amplitude of all modes as well as the phase difference between consecutive modes. The measurement is extremely fast (<10ns) and is adapted to real-time analysis and control of fast signals.

10098-15, Session 4

Injection-locking criteria for simultaneously locking single-mode lasers to optical frequency combs from gain-switched lasers

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Optical sources for the forthcoming terabit/s era of optical communications and networking will require multiple frequency-locked carriers, each with low phase noise, in order to minimize the spectral occupancy of the overall channel bandwidth. One method to construct a highly reconfigurable version of such a source is to use an optical frequency comb from a gain-switched laser to simultaneously injection-lock many different single mode lasers. The outputs from the single-mode lasers are all mutually frequency locked and possess the same low-phase noise properties of the gain-switched comb. In this submission, we present numerical simulation results from the entire system of simultaneously injection-locked single mode lasers by firstly simulating an optical frequency comb from the gain-switched laser and then using that frequency comb to injection lock the single-mode lasers. The simulation approach is to use lumped rate equations with the appropriate stochastic Langevin terms for spontaneous carrier recombination and for spontaneous emission. The inclusion of the stochastic terms are vital when identifying the locked states of the entire system. Using the simulator we are able to identify important criteria to maximize the frequency locking range that suppresses the cross talk from adjacent comb lines to greater than 30 dB, and avoiding the carrier-photon resonance of the single mode lasers is vital to achieve such. The relative simplicity of the simulator has the advantage of being exploited within optical communication simulators to predict the communication system performance when using these sources, which would be of advantage to designers of such systems.

10098-16, Session 4

Wideband chaos in hybrid III-V/silicon distributed feedback semiconductor lasers under optical feedback

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The dynamics of hybrid III-V/Silicon Distributed Feedback (DFB) semiconductor lasers are studied under a combination of long and short feedback conditions. The allure of Silicon Photonics lies in the potential for production of low-cost, compact circuits that integrate photonics and microelectronics on a single Photonic Integrated Circuit (PIC) [1], [2]. Such tight integration of optical components increases the risk of short-cavity reflections within a PIC that can destabilize the laser [3]. Using novel III-V/Si DFB lasers, we simulated such reflections by coupling the laser using a cleaved fiber, thus creating a free-space cavity between the laser and the fiber tip. The sensitivity of such devices to this short feedback and its phase is then studied by comparing measurements performed with either a cleaved or a lens-ended anti-reflection-coated fiber, and reveals the modal and temporal dynamics created by the short-cavity feedback. A long fibered feedback cavity is then created within the experimental setup to study the route to chaos of the devices under long feedback as well as the impact of the short feedback's phase on this route. Due to a relatively high relaxation oscillation frequency of 15 GHz and the destabilization of the laser caused by both the short and long cavity; very wide chaos can be achieved when combining both types of feedbacks. This study thus reveals the impact parasitic reflections can have on the characteristics of a DFB in a PIC and how these reflections can affect the dynamics of the laser in a well-known optical feedback scheme.

10098-17, Session 4

Increasing stability by two-state lasing in quantum-dot lasers with optical injection

Stefan Meinecke, Benjamin Lingnau, Kathy Lüdge, Technische Univ. Berlin (Germany)

Semiconductor lasers based upon self-assembled quantum-dots (QDs) are promising sources for applications in optical networks used e.g. for data transmission via optical fibres. Recently their ability to show simultaneous two-state lasing became the focus of diverse investigations, especially for wavelength multiplexing applications or optical switching.

We theoretically study a quantum-dot laser subjected to optical injection from a master laser. The solitary QD laser is capable of two-state lasing in certain parameter regions due to the strong non-equlilibrium carrier distribution induced by the relatively slow carrier scattering processes[1]. Our modeling approach is based on microscopically based rate-equations and goes beyond the constant alpha-factor approximation by including carrier dependent frequency shifts obtained from a full Bloch-equation approach.

Our results nicely reproduce recent experimental results on optical bistability [2]. Further, we show an increase in the dynamical stability of the two-state QD laser if compared to a single-state QD laser, e.g. to a QD

laser with high losses in the excited state. We find that chaotic dynamics predicted for single-state QD lasers under strong and detuned injection completely vanishes if excited state lasing is possible. This phenomenon is surprising, as an increase in the complexity, i.e. the degrees of freedom, stabilizes the device. However, we find the same trend, i.e. a higher susceptibility to perturbations, for QD lasers modelled with constant alpha-factor and thus with less degrees of freedom than our QD laser model.

[1] Röhm et al., IEEE J. Quantum Electron.51, 2000211 (2015)

[2] Tykalewicz et al., Opt. Lett.41, 1034 (2016)

10098-18, Session 4

Self-consistent rate-equation theory of coupling in mutually injected semiconductor lasers

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Mutual injection in coupled lasers causes the effective coupling to become dependent on the individual inversions in each constituent laser. Therefore, locking of coupled lasers is a more complicated nonlinear problem than considered in existing treatments. A simple dynamical theory for coupled lasers, taking into account the self-consistent modification of the coupling mechanism, is not available yet. In rate-equation approaches, inversion-dependent effective coupling is usually ignored. Most existing simulations are based on linear monochromatic analyses and yield some insight into the coupled-mode behavior of these devices, but the frequency locking of the two constituent lasers and the process leading to that, requires analysis of the coupled rate equations for the complex fields and the inversions in the two lasers. Here we report on a self-consistent rate-equation approach in the spirit of ref. [1] for the mutual injection of two Fabry-Pérot type lasers. Application of the theory to the coupled cavity quantum-well semiconductor lasers of ref.[2] yields good agreement with measurements.

[1] R.J. Lang and A. Yariv,"Local-field rate equations for coupled optical resonators", Phys.Rev.A 34 (1986) 2038-2043.

[2] D. D'Agostino, D. Lenstra, H. P. M. M. Ambrosius, and M. K. Smit, "Coupled cavity laser based on anti-resonant imaging via multimode interference", OPTICS LETTERS 40 (2015) 653.

10098-19, Session 4

Large-signal analysis of directly-modulated strongly-injection-locked whistle-geometry ring lasers

Gennady A. Smolyakov, Marek Osi?ski, The Univ. of New Mexico (United States)

We report on large-signal analysis of strongly injection-locked whistle-geometry semiconductor ring lasers. A key feature of the whistle-geometry ring lasers is the asymmetry between the two counterpropagating modes, with the device structure strongly favoring unidirectional operation. The asymmetry between modal losses results in different lifetimes for the two counterpropagating modes. Our previous analysis of directly modulated strongly injection-locked whistle-geometry ring lasers was limited to small-signal sinusoidal modulation with 1% current amplitude with a simple linear gain model. Here we extend this analysis to large signals, taking into account the carrier-density and wavelength dependence of gain.

10098-20, Session 5

In-plane emission of indistinguishable photons by resonance fluorescence on a quantum dot coupled to a photonic crystal waveguide

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The use of indistinguishable photons as flying qubits has been highlighted in recent proposals as the key element in order to perform quantum computation using linear optics. For on-chip quantum information processing, it is desirable that an efficient source of highly indistinguishable photons is integrated within the photonic quantum circuit. Semiconductor quantum dots are excellent candidates as integrated sources, proven by their great efficiency of single-photon and entangled photon pair emission.

Two-photon interference lies at the heart of the proposed protocols for two-qubit quantum logic operations. In order to achieve high two-photon interference visibility, photons need to be indistinguishable in the spectral, temporal and polarization degrees of freedom. For photons generated by carrier recombination in quantum dots, the interaction of carriers with the host material limits the coherence time of the emitted photons, which has a detrimental effect in the two-photon interference visibility. Here, we report the generation and the on-chip transmission of highly indistinguishable photons by performing resonance fluorescence on an InAs quantum dot. The quantum dot is coupled to a photonic crystal waveguide, which provides efficient in-plane photon transmission. The resonant excitation method greatly enhances photon coherence times, which are found to be 15 times longer than the ones recorded using off-resonant optical excitation. Such an enhancement allows us to measure two-photon interference visibilities over 80%, limited by the detector's temporal resolution and experimental imperfections. Our results are supported by our theoretical model for a resonantly-driven two-level system.

10098-21, Session 5

Feedback control of photon-statistics

Nicolas L. Naumann, Sven M. Hein, Manuel Kraft, Andreas Knorr, Alexander Carmele, Technische Univ. Berlin (Germany)

Feedback is a well established method to control the dynamics of nonlinear systems in the classical regime. Recently, the interest of feedback effects in quantum systems has grown, since it has become accessible in devices working in the quantum limit.

Typical examples include microlasers and superconducting circuits. A strong focus of recent theoretical investigations is on the effects arising from time delayed feedback, so called Pyragas control.

After considering closed systems with fixed numbers of excitations, recent progress allows to study also open quantum systems exactly, including external reservoirs to control the excitation number externally.

Here, we use a quantum stochastic approach for modelling open, externally driven quantum optical systems, exposed to time delayed feedback.

The prototypical example is a single coherently driven cavity mode coupled to a Q-bit. We are interested in the power spectrum of the quantum emission emitted from the cavity mode, including its second order correlation function.

By employing time delayed feedback as a means of controlling the photonic degrees of freedom, the spectral signature of the second rung can be amplified in expense of the first rung.

10098-22, Session 5

Spin transport in a Lindblad-driven isotropic quantum Heisenberg spin-chain

Leon Droenner, Nicolas L. Naumann, Technische Univ. Berlin (Germany); Markus Heyl, Technische Univ. München (Germany); Alexander Carmele, Technische Univ. Berlin (Germany)

The discovery of disorder induced localization in the presence of interactions, known as many-body localization (MBL), opened a new field of theoretical and experimental investigations. A common generic model to study such effects is the disordered isotropic Heisenberg spin-chain. In case of strong disorder and in the absence of losses, it is known that such a system exhibits MBL.

Here, we investigate an open spin-chain that is coupled to external reservoirs with focus on quantum transport e.g. electron and holes in a semiconductor. The environment will be treated as Lindblad-reservoirs at the edges of the chain. Furthermore, we investigate long-range coupling between the sites. In order to detect MBL, we focus on the spin-current which is non-zero in the thermal case due to the excitation pumping and shows diffusive or sub-diffusive behavior. Increasing the disorder, the scaling of the current with the length of the spin chain changes.

This scaling proves the transition from a sub-diffusive to a MBL regime, where the current vanishes. Zero DC conductivity is a known diagnostic for MBL and is associated with persistent storage of quantum information. Hereby, we address the question whether open quantum systems always thermalize or keep MBL related phenomena.

10098-23, Session 5

Momentum and rest mass of the covariant state of light in a medium

Mikko P. Partanen, Jukka Tulkki, Aalto Univ. (Finland)

We have recently shown that, as a direct consequence of the fundamental conservation laws of nature and the special theory of relativity, the energy and momentum of light propagating in a medium are carried by a quasiparticle, a coupled covariant state of light and matter. In transparent materials, these quasiparticles, mass-polaritons, have a finite rest mass and the Minkowski form of momentum. For example, in the case of a diamond crystal and a 2 eV photon, the rest mass of the mass-polariton is 10.5 eV/c^2.

The Minkowski momentum and the non-zero rest mass fulfill the covariance condition, which is a direct consequence of the special theory of relativity. The covariance condition is broken if the rest mass is set to zero. Paradoxically, the observation of the Minkowski momentum in an experiment has been interpreted as an experimental proof of the breakdown of covariance. Actually, for the experimental verification of the covariant state of light in a medium, one has to measure both the momentum and the rest mass of mass-polariton.

In this work, we generalize the recently developed covariant electromagnetic theory for continuous media including the mass transfer effect by adding to it the coupling to elastic forces in the continuum. The model is used for quantitative analysis of the mass transfer effect associated with the mass-polaritons. Results are compared with microscopic atomic level simulations making use of molecular dynamics method generalized to account for the forces between induced dipoles and the light field.

10098-24, Session 6

What limits the power conversion efficiency of GaN-based lasers? *(Invited Paper)*

Joachim Piprek, NUSOD Institute LLC (United States)

Shuji Nakamura predicted in his Nobel lecture that GaN-based laser diodes are the future of solid state lighting. However, GaN-lasers still exhibit less than 40% electrical-to-optical power conversion efficiency while some GaN-based LEDs exceed 80% and some GaAs-based laser diodes exceed 70%. This talk investigates the reasons behind the efficiency limitation of GaN-based lasers and proposes an improved efficiency analysis method.

10098-25, Session 6

Effect of out-tunneling leakage on modulation response of double tunneling-injection quantum dot lasers

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Effect of out-tunneling leakage of carriers from quantum dots (QDs) on the small-signal modulation response of double tunneling-injection (DTI) QD lasers is studied. In this novel type of semiconductor lasers, as an alternative to conventional pumping, electrons and holes are injected into QDs by tunneling from two separate quantum wells (QWs) located on the opposite sides of the QD layer and separated from the latter by thin barrier layers. While the process of tunneling-injection of carriers into QDs should be fast enough to ensure high modulation bandwidth of the laser, out-tunneling leakage of carriers from QDs (i.e., tunneling of electrons into the hole-injecting QW and tunneling of holes into the electron-injecting QW) is an undesirable process. Hence it might seem that the out-tunneling process should be made as slow as possible (ideally, totally suppressed) to maximize the modulation bandwidth. However, in this work, the modulation bandwidth of DTI QD lasers is shown to be practically unaffected by out-tunneling leakage of carriers from QDs, i.e., the bandwidth can be made high (provided that tunneling-injection is fast) no matter the out-tunneling time. This clearly demonstrates the robustness of DTI QD lasers for high-speed operation.

10098-26, Session 6

Seed laser diodes in pulsed operation: limitations and reliability investigations

Germain Le Galès, ALPhANOV (France); Simon Joly, Univ. Bordeaux 1 (France); Giulia Marcello, Univ. degli Studi di Cagliari (Italy); Guillaume Pedroza, Adèle Morisset, ALPhANOV (France); François J. Laruelle, 3SP Technologies S.A.S. (France); Laurent Béchou, Univ. Bordeaux 1 (France)

Using InGaAs/AlGaAs 1060nm commercial Laser Diodes (LDs) and Laser Diode Modules (LDMs) under high current (> 2A) and nanosecond pulsed conditions offers a large flexibility for fiber Laser seeding applications. Nevertheless, the behavior and long term reliability of these LDs under such conditions is not well established. Our work focuses on determining the reliability of 1060nm seed LDs under such conditions by the extraction of Electro-Optical (EO) characteristics and the monitoring of their evolution during pulsed ageing tests. In this context, two segments of parasitic oscillations (“A” and “B” type) were observed in the optical response of LDs and LDMs driven under such conditions. We measured the threshold current value over which the “A” and “B” type oscillations appeared (IthA and IthB) on three batches of Laser diodes, with different packaging. We observed a strong part-to-part variation in the value of IthA and a package dependency for IthB. We conducted a near-field and a time spectral analysis of the LDs optical responses. A near field widening and a temporal spectral broadening, associated with the occurrence of "A" type oscillations, were highlighted. Step-stress ageing tests were then carried out on three LDMs, with different values for IthA (3.9A, 7A, 11.2A). The module with the lowest IthA value failed after the last aging test (7.5A, 100ns, 200kHz). No variation of the optical power or of the IthA and IthB value were observed on the other modules, which were able to withstand the chosen ageing conditions without any noticeable decrease of their performances.

10098-27, Session 6

Analysis of carrier dynamic effects on frequency response of tin incorporated group-IV alloy-based transistor laser

Ravi Ranjan, Prakash Pareek, Mukul K. Das, Indian School of Mines (India)

In recent years group IV materials (Si and Ge) grab the attention of many researchers to work on low cost mid-infrared (2-5 μm) device [1]. However, the indirect bandgap nature of these materials prevents them to be used as an active optoelectronic device. The band engineering of Ge with ?-Sn provides an opportunity for all group IV direct band gap light emitter device in mid-infrared region [2]. In this perspective, authors have already proposed a theoretical model of such alloy based transistor Laser (TL) for mid-infrared region [3]. The structure of TL is similar to a heterojunction bipolar transistor where a quantum well is inserted in base region which work as an active layer and cause a lasing action, so it can be use simultaneously as a transistor and a laser [4].

In this study, an analysis of frequency response of single QW based Si-Si0.12Ge0.73Sn0.15/Si0.11Ge0.73Sn0.14 n-p-n TL is reported. The frequency response of TL for common base (CB) is calculated from small signal relationship between the photon density s(j?) and emitter current je(j?) by solving laser rate equation and continuity equation simultaneously. The results shows that bandwidth of TL in CB configuration is ~4 GHz for 2 mA bias current having zero resonance. The intrinsic response of TL with and without quantum capture and escape effect on modulation bandwidth are also shown. The effects of quantum capture efficiency and carrier recombination lifetime in QW on modulation bandwidth of TL in CB configuration are also address. We absorbed that due to higher quantum capture efficiency and longer carrier recombination lifetime in QW threshold current decreases and modulation bandwidth increases.

[1]. R. Soref, "Mid-infrared photonics in silicon and germanium" Nature Photonics 4, 495-497, 2010.

[2]. J.Kouvetakis et al., Annual Review of Materials Research., vol.36, pp.497-554, (2006).

[3]. Ravi Ranjan and Mukul K Das "Theoretical estimation of optical gain in Tin incorporated group IV alloy based transistor laser" Optical and Quantum Electronics, Vol.48, Article no. 201, March 2016.

[4]. M. Feng, N.Holonyak, Jr., G. Walter, and R. Chan, "Room temperature continous wave operation of a heterojunction bipolar transistor laser" Appl. Phys. Lett. 87, 131103 (2005).

10098-28, Session 7

Investigation of light extraction efficiency comparison of AlGaN-based deep- and mid-ultraviolet flip-chip light-emitting diodes with patterned sapphire surface

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Nitride-based ultraviolet (UV) emitters have attracted substantial attentions for various applications due to compact sizes and higher energy efficiencies. Despite the remarkable improvement in external quantum efficiency (?_EQE) for near-UV LEDs, typical ?_EQE for planar mid- and deep-UV LEDs is still low (<10%). One of the primary reasons for such low ?_EQE is the strong anisotropic emission due to dominant transverse-magnetic (TM)-polarized output in high Al-content AlGaN QWs while conventional planar LED structure favors extracting the light traveling along c-axis. Previous experimental study has shown that dome-shaped patterning on sapphire surface of flip-chip mid-UV LEDs can lead to 50% increased output power. However, very limited studies have investigated the polarization dependence of the ?_extraction, which is particularly critical for conventional AlGaN QWs deep-UV LEDs with TM-dominant emission and mid-UV LEDs with transverse-electric (TE)-dominant emission.

Here, we investigated the TE- and TM-polarized ?_extraction of AlGaN-based flip-chip UVLEDs emitting at 230nm and 280nm with dome-shaped-arrays patterning on sapphire surface based on three-dimensional (3D) finite-difference time-domain (FDTD) simulations. Our results show that dome-shaped patterning is predominantly beneficial in extracting TM-polarized output where 1.06-times and 1.25-times TM-polarized ?_extraction can be achieved for 230nm and 280nm UVLEDs respectively as compared to planar sapphire structures. Conversely, very minimal TE-polarized ?_extraction enhancement (<1%) can be obtained from 280nm UVLED while the dome-shaped patterning is resulting in more TE-polarized photons trapping for 230nm UVLED. Thus, it is expected that this study will shed light on further optimizations of flip-chip UVLED designs for both deep-UV and mid-UV regimes.

10098-29, Session 7

Quadrant detector sensitivity and linearity index measurement with Laguerre-Gaussian beams

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Quadrant detectors (QD) are mainly used in research and industries for displacement measurement purposes due to their high sensitivity and accuracy as compared to other photodiode devices. Its scope extends to subnanometer scales and it is also operable at a wide temperature range with fast response frequencies. These properties and advantages make the QD the best candidate for beam displacement measurements.

A growing interest in the field of optics are beams carrying orbital angular momentum (OAM), particularly Laguerre-Gaussian (LG) beams, due to their properties and remarkable applications, which include optical trapping and gravitational wave detection. In such applications, small relative displacements of the LG beams need to be known; this information is obtained using the QD. However, there is a tradeoff between the QD's sensitivity and linearity index which affects its precision.

Several studies on the improvement of sensitivity or linearity index of the QD are mostly restricted with the use of Gaussian beams on a normally configured (untilted) QD. Some show the sensitivity response of a tilted QD but only for non-OAM beams.

This study shows the combined effect of using different OAM modes of LG beam and varying angles of inclination of the QD, on the sensitivity response and linearity index of the QD. In general, it was observed that a lower OAM value for the LG beam gives a higher sensitivity for the QD and a higher angle of inclination leads to a higher linearity index. This result gives a larger range of application for the QD.

10098-30, Session 7

Modeling and design of DBR fiber lasers for sensor applications

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We present a design technique addressing DBR fiber laser sensors. Modeling such lasers requires solving several critical simulation challenges. The laser cavity provides optical feedback where light experiences hundreds of round trips. The corresponding simulation schematic represents a network of elementary building blocks where the optical feedback introduces feedback loops requiring an iterative approach. We show how the cavity characteristics can be simulated in the frequency or time domain and compare their effectiveness. The design of digital filters accurately reproducing the grating spectra is one important challenge. For DBR lasers to oscillate in single mode the grating selectivity needs to be high enough, which may require a response length exceeding reasonable simulation windows by far.

Furthermore, we discuss how to simulate the entire laser including an amplifying medium. We compare approaches using a system-level amplifier model, stationary and dynamic doped fiber models. We show that for an adequate description of the laser spectrum, modal and noise characteristics the time domain approach in combination with a dynamic fiber model is desirable. The frequency domain approach is problematic due to varying noise samples in each iteration. Note, due to the slow population dynamic in doped fibers tens or hundreds of thousands of iterations may be needed to achieve stationary operation. Once this is accomplished, the laser shows a single-mode spectrum with linewidth in agreement to the quantum limit. Using our developed model we show how the laser characteristics depend on the grating frequencies and can be used for sensor applications.

10098-31, Session 7

Characterization and modelling of multimode optical fiber for MOEMS applications using the elementary source method

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Multimode fibers are used extensively in many applications including optical illumination, sensing, imaging, and spectroscopy. Recently many optical MEMS applications reported the use of MM fiber for delivery of the optical beam to the MOEMS component to make use of its high throughput and thus higher power carrying capacity. In such applications the spatial distribution and the spatial coherence of the output beam from the MM fiber affects greatly the performance of the optical components, especially if the beam is launched in an optical interferometer. However, detailed rigorous modelling of the output profile of the multimode fiber is quite critical as it depends on the input excitation as well as the propagation effects in the fiber. The reported models are usually based on the assumption of a Gaussian profile, which is not necessarily satisfied in many cases such as the bell-shape or donut-shape profiles. In this work, we present a new model for the MM fiber output in which the output beam is considered as a quasi-homogeneous shell source decomposed to its coherent elementary functions. The elementary functions are considered incoherent with each other and are obtained using the inverse Fourier transform of the square root of the radiant intensity, while their weights are obtained from the source end intensity. Experimental results are obtained for multimode fibers with core/cladding dimensions of 62.5/125 ?m, 200/220 ?m and 400/440 ?m. Different fiber excitations are exercised using HeNe laser, Green LED and white light. The radiant intensity is recorded by measuring the far field directly using CMOS camera while the near field fiber intensity is measured by imaging the fiber end using an objective lens. The model shows very good agreement with the measured intensity distribution at different propagation distances.

10098-33, Session 8

Monolithic integration and epitaxial gain control of GaAs nanowire lasers on silicon *(Invited Paper)*

Gregor Koblmueller, Benedikt Mayer, Thomas Stettner, Bernhard Loitsch, Michael Kaniber, Gerhard Abstreiter, Jonathan J. Finley, Walter Schottky Institut (Germany)

We demonstrate a novel monolithic integration scheme for high reflectivity, low-order fundamental modes in GaAs-based NW lasers directly on Si. Essentially, by employing thick dielectric SiO2 mask layers for site-selective growth we create vertical-cavity NW lasers with high spontaneous coupling factors of ? = 0.21. [1] Characterization of the temporal emission dynamics reveals that these NW lasers are capable of ultrafast emission down to < 3 ps, equivalent to repetition rates of > 250 GHz.

In addition, we investigated nanostructured gain media inside the NW lasers to control gain, threshold power density and temperature stability. We present single-mode lasing from radial single and multiple GaAs quantum wells (QWs) in a GaAs-AlGaAs core-multishell NW when subject to optical pumping. The lasing performance shows a reduced threshold power density for 7 coaxial QWs compared to a single QW in a NW with the same diameter, confirming that gain characteristics can be optimized by epitaxial design. [2] Temperature-dependent investigations show that lasing prevails up to 300 K.

We also show that the NW lasers not only operate under pulsed, but also under continuous wave (cw) excitation. Here, ~4x lower equivalent pump power and lower minimum lasing linewidth of ~200 μeV are observed for cw-operation compared to pulsed mode. [3] Remarkably, the NW lasers exhibit negligible heating effects under cw-operation.

[1] B. Mayer, et al., Nano Lett. 16, 152 (2016).

[2] T. Stettner, et al., Appl. Phys. Lett. 108, 011108 (2016).

[3] B. Mayer, et al., Appl. Phys. Lett. 108, 071107 (2016).

10098-34, Session 8

Stabilization of broad area semiconductor lasers

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Broad area semiconductor lasers, which are one of the most useful and efficient light sources, suffer from poor beam quality that limits their applicability. The main reason is the growth of spatial inhomogeneities that develop a transverse multimode output beam with filamentation at high nonlinearities. The homogeneous solution instability, named Modulation Instability, arises from the self-focalization effect and the dependence of the refraction index on the population inversion whose strength is given by the linewidth enhancement factor (alpha) of the semiconductor material. We demonstrate a new method to suppress this instability in such lasers based on a spatial modulation of the pump profile [1].

Recently, it has been shown that a periodical modulation of the potential in transverse and longitudinal space can lead to the control of the Modulation Instability [2]. The periodical modulation creates bandgaps at the unstable frequency range which leads to the elimination of the unstable modes. This stabilization method has been recently applied to stabilize other laser types like VCSELs [3].

Systems with pump rates just above threshold and small enough alpha factors show weak nonlinearities and the frequency band of unstable modes can be covered by the bandgap generated with a single spatial modulation [4]. However, for large alpha factors shown by usual semiconductor materials, multi-frequency spatial modulations are necessary to reach stable

regimes. The optimized parameters of the spatial modulation are obtained through a Genetic Algorithm allowing to stabilize the homogeneous solution for high nonlinearities that correspond to the normal laser operation.

[1] Appl.Phys.Lett. 103, 132101 (2013)

[2] Scientific Reports 5, 13268 (2015)

[3] Phys.Rev. A 92, 043829 (2015)

[4] Opt.Lett. 39, 5598 (2014)

10098-35, Session 8

High-speed directly modulated lasers based on high-order slotted surface gratings

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Directly modulated semiconductor lasers (DML) have the advantages of lower power consumption and higher output power compared to electro-absorption modulator-integrated lasers (EAML). DMLs are important components as sources for short distance communication within 10km or less. In the past few decades, distributed feedback (DFB) lasers were typical DMLs. However, fabricating these DFB lasers requires both high resolution processing and complex re-growth steps. Recently, we have demonstrated the regrowth free single mode lasers by etching high-order slotted surface gratings on top of the ridge waveguide in one side of the laser cavity, where the group of slots provides sufficient reflection for lasing. Such a laser array with 12 channels has been developed. However, for the easy fabrication by standard photolithography, slots with a width of about 1?m are generally used. These wide slots suffer from relative large radiation loss. As a result the laser based on such wide slots has relatively high threshold current ~19mA and low slope efficiency ~0.16mW/mA. In this work, by optimization of the slot parameters a low level of loss of around 10cm-1 is predicted numerically, which is just one fifth of the previous designs. Using the time-domain travelling wave model combined with the 2D scattering matrix method we analyzed the DBR laser based on slots. It was found that the carrier density and photon density distributions were not uniform in the laser cavity. Further we present the design of directly modulated lasers based on slots with a threshold ~5mA, slope efficiency >0.40mW/mA and modulation bandwidth ~40GHz.

10098-36, Session 8

Lasing of metamorphic hybrid 1300nm spectral band VCSEL under optical pumping up to 120 C

Natalia V. Kryzhanovskaya, Eduard I. Moiseev, St. Petersburg Academic Univ. (Russian Federation); Andrey G. Gladyshev, Connector Optics LLC (Russian Federation); Leonid Y. Karachinsky, Innokenty I. Novikov, Connector Optics LLC (Russian Federation) and Ioffe Institute (Russian Federation); Andrey V. Babichev, Connector Optics LLC (Russian Federation); Sergey A. Blokhin, Mikhail Bobrov, Yuri M. Zadiranov, Sergey I Troshkov, Ioffe Institute (Russian Federation); Anton Y. Egorov, Connector Optics LLC (Russian Federation) and ITMO Univ. (Russian Federation)

The ability to create metamorphic hybrid heterostructure of 1300 nm spectral band vertical-cavity surface-emitting laser (VCSEL) is demonstrated. Metamorphic semiconductor part of heterostructure with the bottom GaAs/AlGaAs distributed Bragg reflector (DBR) and 6 InGaAs/InAlGaAs QW active region has been grown by molecular beam epitaxy (MBE) on GaAs substrate. Top dielectric Ta2O5/SiO2 DBR is made by the magnetron sputtering method. VCSEL has been studied under optical pumping (wavelength = 532 nm, diameter of the focused laser beam 1 ?m) by using micro-PL setup in the range of optical pump power 0 – 70 mW at room temperature. Lasing was obtained in the wavelength range of 1291-1299 nm and was observed even for the relatively low optical pump power of 2 mW. Estimations show that lasing occur at the highest optical power of 70 mW applied when the temperature of the heterostructure was about 120oC. Obtained results clearly indicates the opportunity to use metamorphic growth on GaAs substrates for the high-performance 1300 nm VCSEL manufacturing suitable for the operation at high-temperatures.

10098-37, Session 9

Simulation and analysis of quantum cascade lasers *(Invited Paper)*

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In quantum cascade lasers (QCLs), both the spectral gain characteristics and the nonlinear optical properties of the active region can be custom-tailored through quantum engineering of the electronic energy states. By adequate design of the gain spectrum, arbitrary wavelengths in the mid-infrared (MIR) and terahertz (THz) regions can be accessed. Quantum engineering of giant optical nonlinearities enables applications such as the generation of frequency combs and ultrashort pulses, or the realization of widely tunable room temperature THz sources by frequency mixing. For the further development of QCL sources, modeling approaches are required which capture the intricate interplay of the different physical effects involved. Here we review various modeling techniques [1], ranging from semiclassical approaches for the carrier transport, such as the ensemble Monte Carlo method, to quantum transport models. In this context, the adequate implementation of carrier-light interaction will be discussed, which must be included to describe the actual lasing process, and to model the nonlinear effects in QCL sources with giant optical nonlinearities. We demonstrate that by combining various modeling techniques into a multi-domain simulation approach, we can take advantage of their corresponding strengths to significantly improve the reliability and computational efficiency of the simulation tool. As illustrative examples, we will discuss simulation schemes and results for high temperature THz QCLs and high efficiency MIR QCLs, as well as QCL-based frequency comb sources and THz difference frequency generation.

[1] C. Jirauschek and T. Kubis, "Modeling techniques for quantum cascade lasers," Appl. Phys. Rev. 1, 011307 (2014).

10098-38, Session 9

NEMO5: realistic and efficient NEGF simulations of GaN light-emitting diodes *(Invited Paper)*

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The performance of multi-quantum well LEDs is determined by a complex interplay of coherent and incoherent physics: Carriers transit between regions of continuous and discrete density of states. They accumulate energy and momentum in the propagation along electric fields. They face thermalization and momentum randomization in scattering with the heat bath and device imperfections. Even radiative electron-hole recombinations have to compete with nonradiative Auger and Shockley-Read-Hall processes. The nonequilibrium Green's function method (NEGF) is accepted as the method of choice in modeling such situations. It consistently predicts the relative weight of all processes and provides

design guidelines for performance optimizations. However, when the NEGF method is applied in its most consistent description (i.e. in the self-consistent Born approximation), it is numerically too demanding to handle realistically extended LED devices in high energy, momentum and spatial resolution. This work introduces a new approach to LED modeling based on a multiscaled NEGF approach that subdivides the critical device domains and separates the quantum transport from the recombination treatments. Incoherent scattering is modeled in a semi-heuristic way that is carefully benchmarked against detailed NEGF calculations, but requires only a fraction of their numerical costs. First comparisons against experimental data are very promising.

10098-39, Session 9

Novel BPM technique using leap-frog technique

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In this paper we propose a new solution for the wave equation using the BPM technique. The basic idea of this new technique is based on reformulating the BPM equation to separate the real and imaginary parts and utilizes real system matrices only for the propagation steps. The updates equation exploits leap-frog method to couple the real and imaginary parts of the field at each propagation step. We compared our method of solution with the conventional one which is based on assuming the field as a whole term (i.e. complex term without dividing it into real and imaginary) and solving the equation only one. The result of such comparison showed that our technique in solving the BPM equation get a similar result to that of the conventional method however with less processing time showing better processing performance. Our method is proved to be at least 30 % faster times faster than the conventional BPM in solving waveguide problems. Such method can open the door towards efficient computational algorithms for solving complex systems.

10098-40, Session 9

Effect of stacking form, gate voltage, electrostatic screening, and carrier scattering on plasmon propagation in bilayer graphene

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Strong light-matter interaction in graphene enables propagation of plasmons with larger confinement and a propagation length exceeding that of plasmons in noble metals [1]. Contrary to monolayer graphene that exhibits a gapless linear energy dispersion relationship, bilayer graphene shows a quadratic energy dispersion with a finite energy bandgap. This bandgap depends on the difference between the chemical potentials of its two layers and can be adjusted via voltage gating [2], [3], [4]. Moreover, different stacking forms lead to different band structures, and, therefore, different transport and optical properties of bilayer graphene. As such bilayer graphene offers rich physics that can be exploited toward building various plasmonic devices working in different frequency ranges – from terahertz to the infrared – such as antennas, photodiodes, and lasers [4].

By using the tight-binding approach, we calculate the gate-voltage dependent bandstructure for different stacking forms [5], which is used to derive the complex optical conductivity using the Kubo formalism. Effects of electrostatic screening and scattering potentials on the bandstructure and conductivity are also incorporated in the theoretical framework. By solving Maxwell's equations in bilayer graphene, we derive the dispersion relation of plasmons and compare it with that in monolayer graphene. We also study the impact of bandgap via voltage tunability and the stacking orientation on the plasmon propagation characteristics in bilayer graphene. We demonstrate that the gate-voltage tunability of plasmons is enhanced in bilayer graphene compared to that in monolayer graphene, which increases the utility of bilayer graphene to design reconfigurable plasmonic devices.

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10098-41, Session 10

Submonolayer quantum-dot lasers

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Active media based on submonolayer (SML) quantum-dots are a novel gain material that potentially combines the high gain of semiconductor quantum-wells with the ultrafast gain recovery of Stranski-Krastanov quantum-dots. We propose a rate-equation model which describes the intrinsic charge-carrier dynamics of SML devices and shows excellent quantitative agreement with experimentally observed photoluminescence spectra, as well as gain recovery dynamics. The characteristic recovery timescale is found to be well below one picosecond, which we attribute to strong inter-dot coupling between the SML states. Submonolayers are hence shown to possess an intrinsic charge-carrier reservoir, aiding their ultrafast gain recovery [1]. Furthermore, we measure a high optical gain of up to 90 cm-1, which is, however, accompanied by a comparably high frequency chirp.

The performance of semiconductor lasers based on SML active media has received only little attention in the past [2]. We therefore investigate SML lasers by adapting the previously developed rate-equation model, in order to analyze their dynamic properties as well as possibility for high-speed direct modulation. Comparisons with conventional quantum-dot devices show a substantial increase in small-signal bandwidth and large-signal modulation capability.

Our results show that semiconductor submonolayer laser and amplifier devices are promising for high-speed optoelectronics. Their high gain enables further miniaturization, making them suitable candidates for novel integrated photonics applications.

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10098-42, Session 10

Unconventional collective normal-mode coupling in quantum-dot-based bimodal microcavity lasers

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Collective coupling of multiple emitters and the normal-mode splitting proportional to a generalized coupling strength has been observed in many experiments. We analyze the occurrence of a rather unconventional normal-mode coupling in bimodal microcavity-lasers. The effect is attributed to the collective interaction of the cavity field with a mesoscopic number of semiconductor quantum dots as the active medium.

In contrast to the conventional normal-mode coupling appearing in various schemes in the context of the single-particle or collective strong coupling regime, here we observe a hybridization of the cavity modes that leads to a locking of the frequencies and to a splitting of the linewidths in the coherent regime. Vice versa in the incoherent regime splitting of the frequencies and locking of the linewidths is observed.

Our investigations are based on microscopic calculations for a bimodal quantum-dot-laser [1] and experiments that confirm the predictions in the incoherent regime [2]. The transition to the coherent regime is also discussed.

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10098-43, Session 10

Excited state spectral blowup induced by carrier dynamics in the ground state of a quantum-dot laser

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While conventional semiconductor lasers typically emit from a single state, quantum dot lasers based on InAs can be easily induced to emit from the ground state (GS), the first excited state (ES) or indeed from both simultaneously. We experimentally examine such a device with the pump current fixed to give (multimode) ES emission only while in free-running operation. Optical injection into the GS of the laser can induce a switch to single longitudinal mode emission from the GS with complete suppression of the ES. The switching is strongly hysteretic as either the frequency or the power of the master laser is varied. Antiphase oscillations are obtained with periodic short ES pulses appearing with periodic GS dropouts. These oscillations emerge from a homoclinic bifurcation as either the injection strength or frequency is progressively decreased, and finally disappear with complete suppression of the GS and almost free-running, CW emission from the ES. The evolution of the system is marked by a notable expansion of the ES spectrum in the pulsing region. This expansion disappears abruptly when the system switches to the almost free-running ES operation. The phase-amplitude coupling (alpha-factor) of semiconductor lasers plays a dominant role in many nonlinear effects and in multimode dynamics can result in pronounced spectral asymmetry. We find that the spectral expansion cannot be explained with conventional modeling based on individual state phase-amplitude coupling but instead requires the introduction of a phase-amplitude coupling between the two states. Such a coupling is partially related to inhomogeneous broadening.

10098-44, Session 10

Modeling and simulation of the multi-population quantum-dot lasers based on equivalent circuit

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In this article, combined a multi-population rate equations (MPREs) of quantum dot lasers (QDLs) with an equivalent circuit simulation method of multi quantum well lasers, a multi-population quantum dot lasers equivalent circuit model (MPQDLs-ECM) is developed to simulate the lasing, temperature and the turn-on delay characteristics of the MPQDLs. Calculated results show that at the injection current of 11 mA, the GS starts lasing and its output grows with the injection current. As the injection current increases to 22 mA, the ES starts emitting firstly at single energy and broadens into double or triple emission at higher excitations because of the mode competition within the HB. Then the spectra of the QDLs under different temperatures are calculated by using different equivalent HBs. Simulated spectra show that with temperature raises from low to high, the lasing mode of QDs with different energy levels transfer from an independent mode to a coherent mode, leading to the change from a spontaneously wide range lasing to a selectively narrow emitting. Finally, the turn-on delay characteristics are simulated and analyzed. Calculated results show that GS and ES are turned on in three different cases with the excitation goes from the low level to high level: GS is turned on earlier than ES, GS and ES are turned on at the same time, and ES is turned on earlier than GS. All the calculations agree well with other reported experimental and theoretical results, indicating that the MPQDLs-ECM can be of great importance in simulating, analyzing, optimizing as well as predicting the characteristics of the QDs based devices.

10098-45, Session 11

Photonic integrated devices and functions on hybrid polymer platform *(Invited Paper)*

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Photonic devices and functions based on HHI's hybrid integration platform PolyBoard are presented providing features such as low-loss polymer waveguides, InP-based active components, dielectric thin-film elements for compact and efficient wavelength multiplexing or polarization manipulation, and U-grooves and 45° mirrors for passive attachment of optical fibers and photo detectors. Thermo-optical components such as tunable lasers, switches and VOAs have been developed and the possibility of 3D waveguide stacking allows for increasing the complexity and functionality of photonic devices at small footprint. The integration of Graphene layers in the PolyBoard platform enables Gbit/s-operation of electro-absorption modulators for optical interconnects and telecommunications. Actives and passives are fabricated separately, presenting an advantage in yield compared to monolithic platforms at only the cost of requiring assembling the different parts, which can be done nowadays in an automatized way.

10098-46, Session 11

Important parameters of printed polymer optical waveguides (POWs) in simulation and fabrication

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In this paper, polymer optical waveguides (POWs), fabricated by using Flexographic Printing for printing conditioning lines onto polymethylmethacrylate (PMMA) foil substrate material and Aerosol Jet Printing for producing the core and cladding of the waveguide, are characterized by using Monte Carlo raytracing for the scattering process. This method offers the opportunity to simulate the propagation of light which are traced through the produced POWs.

In the first step, the surface roughness of all optical materials which are involved in the fabrication process of the POWs are measured. The roughness measurement of substrate, core, and cladding material is necessary, to interlink the surface roughness (Monte Carlo scattering model) with a nonsequential raytracing method. Not only the surface of each material is investigated, in the next step, the roughness measurement of the interlayer between the printed core and cladding material is examined. To virtually build up the whole manufacturing technology, also the process parameters of the printing need to be investigated. The results of the tracing must be a value of the attenuation of a simulated printed POW to give the designer a feedback about the optical quality of the waveguide before the printing process.

The main goal of the DFG (the German Research Foundation) founded research group OPTAVER is to build up the whole manufacturing process, from the CAD, over the simulation, to the fabrication process and coupling of such printed Polymer Optical Waveguides.

10098-47, Session 11

Fiber based flexure sensor utilizing the sensitivity of evanescent coupling

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Sensing in harsh environments, such as in high magnetic fields like those found within MRI machines or in high-voltage conditions like those found within power transformers lends itself well for the use of fiber optic sensors. Where conventional electronic sensors fail for obvious reasons, specially designed fiber optic sensors can fill in these gaps. The aim of this research was to investigate the feasibility and technical parameters necessary to design a flexure sensor based on evanescent coupling between the modes of a two- (or more) core fiber. The design parameters are discussed and the sensitivity of the sensor is shown to be tunable by modifying variables, such as mode-field size and core spacing, which the coupling constant is sensitive to.

The physical model used to simulate this system is derived from an effective index change due to a combination of strain and an effective path difference which is induced by bending the fiber. The result of this model is a coupled-mode equation that can be systematically solved using an eigenvector approach to mode coupling. With proper fiber drawing techniques, this model predicts measurement sensitivities of curvature down to km^{-1}. Furthermore, this technique can be extended based on simulated long-wavelength measurements to make predictions about where along the length of the fiber the flexing took place. This system has the potential to be used as a competing system for Rayleigh backscattering based flexure measurements.

10098-48, Session 11

High sensitive pressure sensor based on plasmonic Mach-Zehnder interferometer

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In this paper we theoretically realize the all optical pressure sensor using the Mach-Zehnder interferometer (MZI). In this model, one arm of MZI is plated with silver and surrounded with specially design polymer filled metal cylinder with opening at one side where pressure applied. The variation in refractive index changes the phase of the optical signal, which provides the proper relation between the applied pressure and phase of the optical signal. The Surface Plasmon Resonance sensors gives to both the phase and attenuation of the propagating light, this model adjustable to utilize the full range of changes provided by the sensed material. The sensor sensitivity and working range can be increased by optimizing the power entering each branch of the Mach-Zehnder interferometer. The MZI structure can be effectively used to sense surface plasmon resonance and used as an efficient pressure sensor. This paper includes the suitable expressions for the optimizing the power entering each branch of the Mach-Zehnder interferometer, the SPR phase and amplitude changes. The results are very effectively supported by the use of COMSOL and OptiBPM. The proposed model gives high sensitive pressure sensor, including fiber-integrated optoelectronic components, industrial and R&D applications.

10098-61, Session PWed

Multi-parameter fiber optic sensing setup based on spectral-overlap using Fabry-Perot interferometers

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Monitoring of several physical parameters using fiber optics arrangements has received particular attention in recent years. Most of the proposed devices in literature analyze phase or intensity variations to obtain the correct environment information. Moreover, with the purpose of presenting a compact sensing device some authors have proposed an optic fiber structure to detect several parameters, however when a physical parameter is applied over the fiber structure, phase and intensity variations can be observed at the same time, as a result ambiguity detection can occur. Other works use the same modulation (intensity or phase) to obtain simultaneous information; nevertheless, high cost post-processing technique must be implemented to achieve the correct environment information. Another alternative is to generate overlap interference spectrums, where the interacting components generate specific modulation when the physical parameter is applied. These schemes are implemented by an interrogation configuration, which provides simple and low cost signal processing, minimal crosstalk measurement and quasi-distributed multi-parameter detection. Within this context, an alternative multi-parameter fiber optic arrangement based on two all fiber Compact Fabry-Perot Interferometer (CFPI) is presented. Using a 2x1 optical fiber coupler the reflected interference patterns provided by each interferometer are combined, consequently new interference spectrum is generated. This spectrum is affected when curvature and load are simultaneous applied. The load information is obtained through the use of the wavelength

shifting generated by one interferometer, meanwhile the curvature data were analyzed using the intensity modulation provided by the other interferometer. The load analysis presents sensitivity around 0.1nm/N and moreover the experimented curvature shows a resolution of 0.4*10-3cm-1.

10098-62, Session PWed

Measurement of refractive index distribution using micro-lens array based on total internal reflection

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Measurement of refractive index distribution using micro-lens array based on total internal reflection

We present a method based on total internal reflection phenomenon for measuring refractive index distribution with high-precision. In the field of refractive index measurement, the method based on total internal reflection phenomenon is usually used to detect the average refractive index of the surface under tested, but unable to get the detail of refractive index distribution. We proposed a new measurement scheme, using the micro-lens array to split the beam of light. The surface under test is classified as a certain number of tiny detection areas. Through the CCD system, we can get the information of the reflected light. In this measurement scheme, the commonly used methods of differential and reflection boundary are difficult to adapt to a tiny spot detection. Based on this, we modified our refractive index calculation method. We calculated the integral of the light energy distribution. The integral value corresponds to the refractive index value. Through theoretical calculation and the actual scaling, the refractive index value of each tiny area is obtained. Through this method, we applied the existing mature theory of total internal reflection to measuring the refractive index distribution, and achieved the accuracy of 10-4. Additionally, with the measurement surface can be easily extended to a larger one, the proposed method can be also applied to measure the index distribution of biological cells and tissues.

10098-63, Session PWed

Optical J-K flip-flop using switching property of Mach-Zehnder interferometers

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In this study, J-K flip-flop is proposed utilizing electro-optic effect of lithium niobate based Mach-Zehnder interferometers (MZI). J-K Flip flop is most versatile flip-flop amid basic flip-flops. It has vast applications in data storage, data transfer, frequency division, binary counters etc. Lithium niobate ($LiNbO_3$) based MZIs provide both the required bandwidth and the equally important means for minimizing the effects of dispersion. The work is carried out by simulating proposed device with Beam propagation method. The paper also constitutes the mathematical description of device and thereafter simulation using MATLAB.

10098-64, Session PWed

Large area of MCP electronic rinse system design

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In order to enhance the performance of large area MCP (50mmx100mm), electron rinse process needs to be implemented. Electron gain of large area MCP is expected to be tested in this process as well. Based on the study of the current technology of MCP electron rinse and parameters testing, a new electron rinse and testing system with four working stations for large area MCP is developed.

Through the reasonable arrangement of imported molecular pump and ion pump in vacuum System, to ensure that in 40 minutes to reach the vacuum degree of Pa to meet the requirement of electron rinse and test and to reach the ultimate vacuum degree of Pa. In this system, an efficient pumping device ensures that the vacuum system to reach the working environment for electron rinse as soon as possible. While the use of four-station design greatly improves efficiency of electron rinse and test of large area MCP. An electronic surface-emitting source was redesigned in this system. The way it works is that the ultraviolet light source emits a uniform ultraviolet light on the gold cathode with voltage of several hundred volts, thus numerous uniform electrons are emitted from the surface of gold cathode. At the same time,0V ~ 700V adjustable high voltage is adopted between the gold cathode and the standard MCP(diameter of 105mm) to generate an accelerating electric field. After electrons are accelerated by the electric field, the high energy is obtained, and the standard MCP is bombarded. The number of electrons can be exponentially increased and controlled by the voltage applied between the input and output surface of the standard MCP.200v voltage is applied between the output surface of standard MCP and input surface of the MCP to be rinsed to lead the uniform electron beam to bombard the MCP to be rinsed, then the gas molecules and related impurities are cleared out in this process. In the original electron rinse system, which is suitable for the MCP with the diameter of 30mm,uniform emitted electrons are obtained by heating the planar spiral tantalum filament in the thermal electronic surface-emitting source in vacuum System. The largest effective emitting diameter of uniform electrons produced by such a thermal electronic surface-emitting source is 50mm, and it cannot meet the size requirement of the electron rinse of large area MCP. Meanwhile, prolonged use of this thermal electronic surface-emitting source causes the filament oxidation and deformation problems. And complexity of the tantalum filament production process and the design of the accelerating field makes difficult to guarantee the reliability of the uniformity of emission electrons. This successful design of the electronic surface-emitting source in the system not only overcomes the limitation of the thermal electronic surface-emitting source based on tantalum filament in use, but also the analysis of the results of the electronic uniformity testing experiment indicates the electronic uniformity of the electronic surface-emitting source has reached 98%,which is 5% higher comparing to the thermal electronic surface-emitting source based on tantalum filament in use.

10098-65, Session PWed

Spatial filtering velocimetry without tracer substance using linear CCD

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Velocity is undoubtedly a fundamental parameter in daily life. Previous study revealed that the optical velocimetry has the feature of non-interfering, non-contact and high accuracy, which makes this measuring approach welcomed. One of the optical velocimetries, spatial filter velocimetry (SFV) introduced in this paper converts measuring of velocity into measuring of frequency signal instead of getting the displacement per unit time. The signal frequency multiplier a constant factor which is decided by the optical system thus the velocity obtained. In order to set up an experimental devise, we discussed this velocimetry theoretically and obtained requirements for spatial filter (SF) such as the transmission function of it. Furthermore, an experiment based on taking a linear CCD as a combine of SF and photodetector (PD) is proposed, and a lens is also needed for imaging. Analysis of the frequency signal shows that SFV is effective even without a tracer substance to gain the information of displacement, which promise this approach extensive applications. Another attraction of SFV is that a laser as light source is not necessary, which means a broad spectrum light source can meet the requirement. Thanks to advantages mentioned above, we applied this velocimetry to a specific industrial environment where a

small flat moves in plane, and we tested this velocimetry when the velocity is 2.5m/s below and the error of maximum velocity is around 3%-7%. SFV can also be applied to measure the speed of cars and airplanes.

10098-66, Session PWed

Tunable plasmon-induced transparency and slow-light based on graphene metamaterials

Shiwen Luo, Huazhong Univ. of Science and Technology (China); Bin Li, Jun Gao, Anlan Yu, Dongsheng Xiong, Xinbing Wang, Duluo Zuo, Wuhan National Lab. for Optoelectronics, Huazhong Univ. of Science and Technology (China)

Graphene has attracted much attention due to its unique optical properties as a new kind of plasmonic metamaterial in the terahertz regime. Here, we theoretically investigated a wavelength tunable plasmon induced transparency (PIT) device based on graphene metamaterials which is composed of periodically patterned graphene nanostructures. The interactions and coupling between plasmonic modes are investigated in detail by analyzing the field distributions and spectral responses. The coupled Lorentz oscillator models are used to explain the physical mechanism of the PIT. The finite-difference-time-domain (FDTD) method is used to investigate the tunable properties of the structure. It is shown that the coupling strength between the bright mode and dark mode is tuned by the coupling distance between the elements of the proposed structure. By varying the Fermi level of grapheme, the PIT resonant frequency can be dynamically tuned. Furthermore, we demonstrate numerically that tunable slow light can be realized in our patterned graphene metamaterials.

10098-67, Session PWed

Lasing dynamics of microwatt-threshold Raman silicon lasers using high-Q nanocavities

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Only the silicon lasers based on stimulated Raman scattering have been realized. Especially, we achieved a room-temperature continuous-wave Raman silicon laser using a photonic-crystal high-Q nanocavity with a microwatt threshold. The laser utilizes two high-Q nanocavity modes (pump mode and Stokes mode) to confine the pump light and Stokes Raman scattered light into the cavity, respectively. We have thus far studied the fundamental properties for the two nanocavity modes to enhance the performance. However, time-domain measurements to clarify the lasing dynamics have not been performed, which should be very important to improve the device design toward various applications. In addition, various nonlinear effects should be also enhanced due to the two nanocavity modes, which strongly influence the laser performance in the high excitation range.

In this work, the lasing dynamics of nanocavity Raman silicon lasers with a microwatt threshold were studied by time-domain measurements. Above the threshold (Ith), the Stokes Raman laser signal has a long rise time of several ten nanoseconds from the excitation of the pump mode due to the high-Q nanocavity mode. The stable cw lasing was obtained below the input power of 3 ? Ith. Meanwhile, in the high excitation range above 4 ? Ith, the lasing signal oscillated with the period about 40 ns because the signal for the pump mode oscillated due to the change of refractive index by plasma effect and thermo-optic effect. These interesting behaviors were investigated using coupled-mode theory including various nonlinear optical effects, and we obtained consistent results.

10098-69, Session PWed

Solving the nonlinear diffusion model of the ion exchange process using finite element method

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Due to its low cost and simplicity, ion exchange is considered one of the most commonly used processes to produce glass waveguides nowadays. This fabrication technology is based on the substitution of some ions already present in the glass with other ions having different sizes and polarizabilities. A careful study of the resultant refractive index profile is crucial in the impact on the waveguide characteristics. In this paper, we introduce, for the first time, a novel solution of the nonlinear diffusion equation that model this process using finite element method (FEM) approach.

The ion exchange can be modelled as a nonlinear diffusion equation, as the exchanged ions Ka+ diffuse into their new sites where the original ions were existing. Numerical instabilities are encountered when solving for the exchanged ions with similar diffusion coefficients as in the case of Ka+/Na+, which is used in fabricating integrated optical devices with refractive index differences compatible with those of the optical fibers.

Different novel FEM techniques are proposed in solving the problem in both 1D and 2D spaces. The stability and accuracy of the different methods outperforms the current numerical methods and provide a good tool for highly nonlinear diffusion problem.

10098-70, Session PWed

Stabilization of regular pulses utilizing double-delay loops

Ming-Ju Wu, Yu-Shan Juan, Yuan Ze Univ. (Taiwan)

Optoelectronic feedback (OEF) system plays an important role in nonlinear dynamics because of low-cost and easy to generate dynamical states, including regular pulsing (RP), quasi-pulsing (QP), and chaotic pulsing (CP). However, the non-ignored noise naturally generated by delay-loop frequency in the dynamical states is the most important problem to be solved. In this paper, we focused on the generation of RP states and also on the improvement of the noise reduction in the RP states by utilizing the double-delay system. The double-delay system is built up by optical feedback (OF) and OEF systems. When adjusting four controllable parameters of OEF delay time, OEF feedback strength, OF delay time, and OF feedback strength, more complex dynamics are obtained compared to those observed in individual OF and OEF system. Moreover, noise reduction of the RP states caused by the mixing of delay loop frequencies in double-delay scheme is realized by applying an additional OF delay loop to the already-generated RP states by OEF scheme. To explore the quality of the generated RP states, the measurements of amplitude variation in time series and the single-side band phase noise in frequency domain are examined. As a result, effective noise reduction in RP states is achieved while applying a weak OF feedback strength and a short OF delay time. Furthermore, no common factor in these two delays is necessary to observe stabilized RPs and the amplitude variation down to 0 which is equal to 100% noise reduction is achieved while fine-tuning the controllable parameters carefully.

10098-71, Session PWed

Generation of broadband chaos and stabilized regular pulses by quasi-periodic states in dual-feedback system

Ting-De Liao, Yu-Shan Juan, Yuan Ze Univ. (Taiwan)

Nonlinear dynamics of semiconductor lasers under individually optoelectronic feedback (OEF) and optical feedback (OF) is attracted much attention in these two decades. However, according to my knowledge, there is no related research results in dual-feedback system composed of optical and optoelectronic feedbacks. In this paper, the nonlinear dynamics of the dual-feedback system is studied and applications in generation of broadband chaos and stabilized pulses based on quasi-periodic (QP) states are achieved. Generally, QP states do not have contributed application which limited the research attention in recent years. Here we focused on the QP state and turned it to be the useful chaos and pulses. The QP is firstly generated by pure OEF system and then applying an additional OF system to obtain the chaos and pulses by tuning the controllable conditions of feedback strength and delay time. To explore the rich dynamics of the dual-feedback system, mappings of each dynamical states are calculated, including regular pulsing, periodic oscillation, and chaotic oscillation and pulsing states. Furthermore, chaos bandwidth and amplitude variation of regular pulses are examined to quantify the signals generated. A 4-fold improvement of chaotic oscillation frequency is observed in dual-feedback system compared to the chaos generated by pure OEF system. A bandwidth of 32 GHz of chaotic oscillation is obtained in dual-feedback system when using a relaxation oscillation frequency of 2.5 GHz laser in the free-running condition. Moreover, the improved percentage of averaged amplitude variation in regular pulses is around 81.6% compared to those generated by pure OEF scheme.

10098-72, Session PWed

Low-loss graphene-based electrically-modulated vertically-coupled directional coupler

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Fast, compact, integrated electro-optic modulator is one of the key component of future computing. Graphene, a new two dimensional material with interesting electro-optical properties, enabled many recently developed compact electro-optical switching techniques. Most of them, however, rely on optical absorption variation to modulate incoming lightwave signals. In those devices, thermal buildup resulting from such optical absorption could present a fundamental limit preventing future very-large-scale integration of millions such devices onto a single electro optical integrated chip. An interferometer based optical switch could potentially operate without such optical loss. However, such devices are quite large.

Recently, it has been numerically demonstrated that by adding doped graphene to a frustrated total internal reflection (Graphene-assisted FTIR) configuration, it is possible to control the evanescent wave coupling in a nearly lossless fashion at a wavelength near the epsilon near zero (ENZ) region of graphene. In this paper, a compact vertically coupled directional coupler based on the graphene-assisted FTIR is designed and its performance as an optical modulator is numerically demonstrated. In the designed device, the graphene-assisted FTIR structure is embedded between two waveguides, and the properties of the supermodes and the resulting coupling length are electrically controlled. Relying on the strong modulation of the evanescent coupling in the graphene-assisted FTIR, an extingtion ration of 24 dB was achieved in a compact device of 3?m by 1?m.

The designed compact, low loss, vertically coupled directional would be an important component acting as a switchable router between layers in fully scalable 3D electro-optical integrated circuits.

10098-73, Session PWed

Computer modeling and approximation of laser beam reshaper based on aspherical optics

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Nowadays, laser radiation is used in most optical systems, because of its special features such as high light coherence, narrow directivity, high power, narrow spectral range of emission which are very important in many research and design issues. Many technical applications need laser beam reshaping, which represents redistribution of optical power in the beam cross-section; particularly to form a flat-top beam.

Traditional telescopic lens systems, which are used for the laser radiation collimation, do not allow to achieve laser beam reshaping. To solve this problem more complicated optical systems with aspherics surfaces are used. Such surfaces synthesis requires to develop a specific mathematical model that could be installed then into special commercial software.

This work describes laser beam reshaper modeling using two aspherical lens telescopic system. Also are shown approximation equations of refractive aspherical surfaces and the reshaping optical system model applying Zemax software.

10098-74, Session PWed

Surface plasmon-enhanced light emission in near UV regions using aluminum nanorings fabricated on AlGaN/InGaN multiple quantum wells

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Near-ultraviolet (NUV) light-emitting diodes (LEDs) have been used in many application areas such as biological detection, counterfeit bill detection, medical equipment and water/air purification system. However, the internal quantum efficiency (IQE) of NUV-LEDs is still much lower than those of blue and green LEDs because it is strongly influenced by the nonradiative recombination process via threading dislocations and other defects in crystal structures. Much research has been performed to improve the IQE of NUV-LEDs by enhancing crystal quality; however, we need to investigate another method to enhance the IQE, such as localized surface plasmon (LSP), in the NUV region.

In this study, we demonstrate that the light emission from AlGaN/InGaN-based multiple quantum wells (MQWs) can be significantly enhanced when the light waves generated in the MQWs are coupled to energy-matched LSP using Al nanoring structures. Compared to bare MQWs, the ratio of emission enhancement of 227% in peak PL intensity was obtained. To investigate the IQE and carrier dynamics of recombination, we also carried out the temperature-dependent PL (TDPL) and time-resolved PL measurements. As a result, the PL efficiency at room temperature for structure with Al nanoring was calculated as 33% (without Al nanoring ~19%) indicating a high IQE due to energy-matched LSP. Also, a radicative lifetime was calculated as 0.63 ns (without Al nanoring ~1.24 ns) at room temperature, which plays an important role in enhancing overall optical properties in MQWs with Al nanoring structures. More details on the electroluminescence and simulation results will be presented at the conference.

10098-75, Session PWed

Coaxial fiber as a first order dispersive media for pulse repetition rate multiplication

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A coaxial fiber is a cylindrical coupled waveguide structure consisting of two concentric cores, the inner rod and an outer ring core. In such a configuration, the dispersion characteristics of the LP01 and LP02 supermodes show an extremum at wavelengths which depend on the structural parameters. Hence, the selective excitation of any one of such mode can be used to achieve temporal Talbot effect for pulse repetition rate multiplication (PRRM) in high bit rate optical fiber communication. We have designed the coaxial fiber to obtain Group Velocity Dispersion (GVD) extremum at the standard communication wavelength of 1.55 μm for the mode with higher excitation coefficient i.e., the LP02 mode. A GVD of -100.795 sq(fs)/mm is obtained for this mode and the corresponding Talbot length (zT) is obtained as 986.9 m. We analyzed the propagation of a sequence of Gaussian pulses through this coaxial fiber and compared it with the propagation of the pulse train through the corresponding ideal first order dispersive media. It is observed that for an input Gaussian pulse train with pulse width, 2?0=1ps at a repetition rate of 40 Gbps (repetition period, T=25 ps), an output repetition rate of up to 640 Gbps can be achieved without significant distortion with the specifically designed coaxial fiber at a length of zT/16=61.68 m. We have also shown that the length tolerance for PRRM is of the order of a few centimeters and can be easily achieved practically.

10098-76, Session PWed

Recrystallization of nano bars on HgCdTe surface treated by ion implantation, chemical etching, and high temperature annealing

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The recrystallization of the nano bars on the surface of HgCdTe LPE and MBE epilayers treated by ion implantation, wet chemical etching and Hg overpressure annealing at high temperatures was discovered. The HgCdTe epilayers were grown on the CdZnTe and Si substrates by LPE and MBE, respectively. Then, all the samples were coated by CdTe films and implanted selectively by As ions at 360keV; before Hg overpressure annealing, the samples were etched by the HNO_3/HF/$K_2Cr_2O_7$ and H_3PO_4/H_2O_2 solutions, respectively; Finally, the high temperature annealing was performed on the samples at 420°C and 240°C.

By SEM, TEM, AFM and EDS, the microstructure and component of these nano bars were characterized. The results indicate that the growth of these nano bars is along specific orientations and their component is close to that of the epilayers. Compared to the un-implanted n-type samples, there is almost no nano bar forming on the surface of the implanted p-type samples. Both nano bars and pits are distributed on the samples treated by the HNO_3/HF/$K_2Cr_2O_7$ solution, while neither of them occurs to the samples treated by the H_3PO_4/H_2O_2 solution. The conclusion shows that the epitaxial growth method, ion implantation, chemical etchant affect the recrystallization process induced by Hg overpressure annealing.

10098-77, Session PWed

Two-dimensional modeling of AlInAs avalanche photodiodes for high gain-bandwidth product

Yegao Xiao, Zhiqiang L. Li, Michel Lestrade, Simon Li, Crosslight Software Inc. (Canada)

High speed optical receivers are in demand due to increasing growth of data traffic in optic fiber network systems. AlInAs avalanche photodiodes are attracting significant interest due to their demonstrated high gain-bandwidth product with low excess noise factor as well as their reliability and stability for large volume of component manufacturing. In this work, two-dimensional modeling of planar junction AlInAs avalanche photodiodes is reported. Modeling results of dark/photo current, multiplication gain, breakdown voltage, -3dB bandwidth and gain-bandwidth product etc are presented. The modeling results of multiplication gain and -3dB bandwidth are consistent with reported experimental demonstration. Design optimization is also explored for higher gain-bandwidth product for such AlInAs avalanche photodiodes.

10098-79, Session PWed

(2+1)D self-trapped light propagation in a quadratic Kerr composite

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Nowadays one of the most relevant problems to solve in soliton optics is related to the search for new materials; that can support stable propagation of multidimensional spatial solitons, as well as spatiotemporal solitons. Furthermore, those new media must allow logical operations with solitons. During the last years, a significant evolution in man-made materials is observed. It is of crucial interest the possibility to manage the nonlinear optical properties of such media that could be able to support the multidimensional soliton interaction for commutation purposes. Here we examine another type of man-made material constructed by nanometric thickness layers of different materials, in our case one medium has a Kerr nonlinear response and the another a Quadratic one; we call this media Quadratic-Kerr Composite (QKC). In this work we study, both theoretically and numerically, the properties of the nonlinear light propagation and interaction in a QKC. We obtain the effective nonlinear optical susceptibility of the composite, which allows developing the nonlinear propagation equation for the slowly varying electric field envelope. Using variational methods, we find out the ansatz for the self-trapped solutions in the (2+1)D case. Applying numerical experiment techniques, we demonstrate the stable beam propagation and some interaction properties.

10098-80, Session PWed

Highly accurate scanning attachment for SRS-lidar system

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Was developed highly accurate scanning attachment for SRS - lidar system. The module performs automated scan of the test area in the angular field of ± 50 on 50-100 m distance. Movement of the laser beam in a spiral occurs due to rotation in one direction wedges with different speeds, which speed is in the range of 50-200 Hz. The rotation is carried out using stepper motors FL-28, with a minimum value of 9.5 second step. The stepper

motor is controlled by a dedicated controller, communication with which is organized on the principle of “command” - “A” using the Modbus RTU protocol. Management Software scanning unit is implemented using the C # programming environment. The position sensor is fixed by means of wedges of angular rotation up to 15 ‘in real time and transmitted to the software module for SSI interface at speeds up to 20 Mbps. An important advantage of the developed software and hardware is a function of rotational speed correction pair of optical wedges as you progress through the trajectory, which provides for a known distance and the divergence of the laser sensing study the lack of “blind” over the entire field of view area. In this case, the laser beam had a divergence of 1.5 mrad. Because the spatial resolution at the outer coils falls compared with the center spiral wedges speeds ratio increases from 0.8 to 0.97, respectively.

10098-81, Session PWed

Optoelectronically controlled Fresnel lens in twisted-nematic liquid crystals

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The opto-electronically controlled Fresnel lens in twisted-nematic liquid crystals (TN-LCs) with a photoconductive layer has been demonstrated in this study [1]. A dc voltage was applied to the cell with a photoconductive polymer layer on one substrate irradiated using a Fresnel zone pattern obtained from a Sagnac interferometer [2]. The application of an external dc field causes the accumulation of ionic impurities on the substrates, which forms an internal field in the opposite direction to reduce the effective electric field in the cell, thereby increasing the external threshold voltage required for the reorientation of the LC molecules. Irradiating with light of an appropriate wavelength, the photoconductive polymer layer became conductive and increases the effective electric field in the bright zones of the Fresnel pattern. The difference of effective electric fields between the bright and dark zones of the Fresnel pattern led to a discrepancy in the reorientation of the LC between adjacent zones. The intensity of the Fresnel pattern and external dc voltage can both be used to tune the diffraction efficiency by changing the difference in LC configurations of the bright and dark zones. The maximum diffraction efficiency of 28% is occurred in the applied voltage of 1.4 V and the average irradiated intensity of 11.7 mW/cm2. The rise time and fall time are approximately 0.5 s and 1.2 s, respectively. The proposed device has the potential to provide dual-controllability in photonic applications.

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10098-82, Session PWed

Optimization of micro channel heat sinks for high-power 9xx-nm laser diodes

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High power laser diodes have found a wide range of industrial, space, medical applications, characterized by high conversion efficiency, small size, light weight and a long lifetime. Thermal management of high power lasers is critical since the junction temperature rise due to large heat fluxes affects the device characteristics. In this investigation, high power 940 nm laser bars were mounted on optimized micro-channel heat sinks (MCC) using AuSn/CuW and In Soldering schemes. The optimized MCC cooler has increased heat-sinking capability which has been confirmed to the simulation results. The improvements in thermal and strain characteristics will be reported through wavelength, thermal rollover, spatial spectrum, smile, and polarization.

10098-83, Session PWed

A novel biasing dependent circuit model of resonant cavity-enhanced avalanche photodetectors (RCE-APDs)

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In Resonant Cavity Enhanced Photodetectors (RCE-PDs), the trade-off between the bandwidth and the quantum efficiency in the conventional photodetectors is overcome. In RCE-PDs, large bandwidth can be achieved using a thin absorption layer while the use of a resonant cacvity allows for multiple passes of light in the absorption which boosts the quantum efficiency. In this paper, a complete bias-dependent model for the Resonant Cavity Enhanced-Separated Absorption Graded Charge Multiplication-Avalanche Photodetector (RCE-SAGCM-APD) is presented. The proposed model takes into account the case of drift velocities other than the saturation velocity, thus modeling this effect on the photodetector different design parameters such as Gain, Bandwidth and Gain-Bandwidth product.

10098-49, Session 12

Advances in spatially-variant photonic crystals

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In the present work, an algorithm was developed to bend, twist, and functionally grade periodic structures while minimizing deformations to the unit cells in ways that weaken or destroy the optical properties of the lattice. The algorithm is not based on spatial transforms because this approach inherently produces deformed lattices. Instead, the lattices are generated numerically as a best fit in order to minimize deformations. This work describes the algorithm and reports recent improvements and applications. The first demonstration of a geometry-conserving spatially-variant lattice was a self-collimating photonic crystal that was designed to flow an optical beam through a 90° bend. Although the photonic crystal was created using a photopolymer with a refractive index of only 1.59, it was capable of directing light through a turn with radius as small as 6.7?0, which is the tightest bend ever reported in the literature. In later work, a band gap photonic crystal was spatially varied to sharply bend a multimode waveguide. The three lowest-order modes were shown to propagate around the bend without any intermodal coupling. Other applications are reported for use in integrated optical systems.

10098-50, Session 12

Optical propagation in anisotropic metamaterials

Rudra Gnawali, Partha P. Banerjee, Univ. of Dayton (United States); Dean R. Evans, Air Force Research Lab. (United States)

Anisotropic metamaterials are widely used in the field of optics because of their unique electromagnetic properties. These metamaterials can be made from multilayer metallo-dielectric structures. Such stacks can be represented as an anisotropic bulk medium using effective medium theory. Optical properties of anisotropic media are mostly described in terms of effective parameters such as permittivity and permeability, or alternatively,

refractive index and characteristic impedance. These properties depend not only on the wavelength and polarization but also the direction of the optical wave-vector. In this work optical wave propagation through such anisotropic media is studied in detail. The Berreman 4 ? 4 matrix along with appropriate boundary conditions is used to analyze all electric and magnetic fields inside and outside the structure. The overall transmission and reflection are investigated as a function of the thickness of each layer (metal/dielectric), number of layers, wavelength, and the angle of incidence. The validity of the effective medium theory is also investigated by changing the thickness and number of layers.

10098-51, Session 12

Numerical modeling of photoluminescence in anisotropic nano-layered aluminum-doped zinc-oxide metamaterial with hyperbolic dispersion

Evan Zarate, Natalie Best, Priscilla N. Kelly, Lyuba Kuznetsova, San Diego State Univ. (United States)

Aluminum-doped ZnO (AZO), a wide direct bandgap semiconductor which emits laser light in the ultraviolet range at room temperature, presents a promising optical gain material for creating lasers for applications in photonics, information storage, biology and medical therapeutics. AZO exhibits an excitonic photoluminescence peak in the ultraviolet region and a defect related photoluminescence peak in the visible region. In addition, recently developed [1] aluminum-doped ZnO nano-layered structure has a unique optical property namely that the dispersion of the dielectric constant exhibits an optical topological transition in the isofrequency surface from an ellipsoid to a hyperboloid. This unusual optical property provides a unique opportunity for creating nanoscale cavities with dimensions significantly smaller than the wavelength of light [2] which could lead to potential applications as efficient and compact ultraviolet lasers and LEDs.

In this work, we investigate the photoluminescence properties of the anisotropic nano-layered aluminum-doped zinc oxide. In order to describe the influence of the aluminum dopants, a complete model for photoluminescence based on the set of rate equations for electron-hole recombination is developed. The set of coupled rate equations is solved numerically using the fourth order Runge Kutta technique for various optical pump intensities. Our calculations predict that the near-band-edge intensity increases with the addition of aluminum (aluminum filling factor ~3%), which indicates that the band gap energy increases as the aluminum content is increased. Experimental results for photoluminescence of the recently developed nano-layered aluminum-doped zinc oxide metamaterial will also be discussed.

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10098-52, Session 12

Study of the phononic band-gap of TiHx by INS test

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The concept of the hot carrier solar cell (HCSC) is to collect the high energy photo-generated carriers before they completely thermalise. The absorber of HCSC should be able to maintain these hot carriers for a long time. Decay of optical phonons to acoustic phonons is usually dominated by one optical phonon decaying into two acoustic phonons, also known as Klemens decay. It has been predicted that a material with a large phononic band gap - enough to block Klemens decay - should have considerably slow carrier cooling speed. Binary compounds with large mass ratio between the constitutional elements likely contain large phononic band gaps. Thus, the binary hydrides are potentially important candidates for the absorber of HCSC, due to the low mass of hydrogen. Transition metals generally form metallic hydrides among which TiHx does not react with water or air at room temperature. Its stoichiometric form has been predicted to have a large phononic band gap by DFT. However, no experiments have been conducted to support it. A bulk polycrystalline TiH1.65 has been made by directly hydrogenating a bulk Ti. Inelastic Neutron Scattering (INS) tests have been used to study its phonon density of states (PDoS). A large gap in the PDoS has been identified. Low energy peaks (presumably acoustic phonons) are an excellent match for energies calculated by DFT. The high energy peak (most likely optical phonons) is lower than modelled, which is suspected to be caused by the nonstoichiometric form of TiHx sample and possibly oxygen impurity. Further discussion of the results and implications for TiHx as an absorber material will occur at the conference.

10098-53, Session 13

Stopped microwave-rainbow in chirped photonic crystals

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The reported “stopped rainbow” concept in tapered metamaterial [1] and plasmonic [2] guiding microstructures has revealed the possibility to obtain local wave enhancement together with spatial chromatic resolution. Recently, this phenomenon has also been demonstrated in graded defect waveguides in photonic crystals [3]. As the wave is stopped in such single mode defect waveguides, the energy of the stopped wave will be restricted due to the limited volume of the mode, which seriously limits the “brightness” (i.e. its local intensity) of the trapped rainbow. For many applications more desirable would be to stop the light in a bulk of a structure, and to harvest the energy of the stopped wave across all the structure, without any principal restrictions imposed by the mode volume. Such stopping of waves in bulk of a structure has been shown for acoustic waves in sonic crystals recently [4] and also for electromagnetic waves in multilayer dielectric slabs [5]. However high radiation losses in the latter case are inevitable due to the weak index confinement. Here we present a first experimental demonstration of stopped microwave in a chirped 3D photonic crystals. We show that the complete 3D photonic bandgap may significantly reduce the external losses and we also show that the local intensity can be enhanced up to two order of magnitudes. This allows an important increase of absorption/photodetection of microwave radiation. We further demonstrate that the different microwave components stop and reflect at different depths of the chirped structure, which offers a frequency-resolved microwave detection.

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10098-54, Session 13

Numerical modeling of evanescent oxide-waveguides for different input spatial soliton solutions

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Modeling of two initial soliton solutions A sech(x), A sech(x/w) in a rectangular evanescent waveguide is carried out where w is the pulse width at a particular input wavelength. The incorporation of a width parameter in a spatial soliton solution reduces the dispersive nature of solitons, making them more stable while propagation. A relationship between the input wavelength and pulse width is necessary for a continuous solitonic path. Studies were carried out for different refractive index materials such as MgO, ZnO, doped ZnO and TiO2 and compared with triangular refractive index profile for the same parameters. Lower refractive index materials exhibit an oscillatory nature for the propagating soliton while in higher refractive index materials, a continuous non-oscillatory profile was observed. A higher index contrast and larger core geometry has the additional advantage of confining more light in the core region and allowing minimum light seeping into the cladding layers. Therefore, a balance between the waveguide width (dispersive factor) with input wavelength and core refractive index (nonlinearity) adds to stable solitonic propagation. The occurrence of a localized well-confined guided mode is an evidence for the possibility of soliton propagation in higher index oxide cores. Corresponding mode-field distributions for the different waveguide structures are plotted along the spatial directions x, y, z. Realization of such structures may be useful for low loss, distortion-less nonlinear optical communication channels and evanescent sensors.

10098-55, Session 13

Modeling and analysis of scattering from silicon nanoparticles with high excess carriers for MIR spectroscopy

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In this work a detailed analysis of the scattering cross-section from highly doped silicon Nano-particles in the near and Mid infrared (MIR) is provided .The effect of different radii of the on the resonance peaks is studied using Mie theory and verified using FDTD. The effect of the doping level on the scattering cross section also analyzed. The study reveals many useful characteristics for such particles which behaves as plasmoinc particles in the MIR. Using this study, different particles are designed as scatters in the MIR based on specific dimensions and dipping level. These particles are utilized for infrared spectroscopy of different application such as gas and biomedical sensing in the MIR.

10098-56, Session 13

Device design for global shutter operation in a 1.1-um pixel image sensor and its application to near-infrared sensing

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Global shutter is a feature of CMOS image sensors that allows capture of an entire image at a single point in time. It is especially important for active illumination infrared sensing in outdoor settings, such as collision avoidance and iris and face recognition, because it aids the rejection of bright background light and reduces power consumption. Whereas conventional CMOS sensors achieve global shutter by adding an extra transistor in to pixels of 3 μm or larger, InVisage's QuantumFilm enables a new type of global shutter that operates by controlling the bias on the QuantumFilm device stack. QuantumFilm is a proprietary semiconductor made from semiconductor nanoparticles, developed by InVisage Technologies for use in a 1.1 μm pixel CMOS image sensor.

In this presentation, we discuss how the device architecture of QuantumFilm enables global shutter operation with high shutter efficiency. High shutter efficiency is particularly important in high dynamic range scenes where the "off" state must be achieved over a wide range of biases. Our approach uses specially designed carrier-selective layers in our device architecture.

We use drift-diffusion device simulations to inform our design and reveal device and material properties that are key for carrier selectivity. Based on our device model, we fabricated global-shutter-enabled QuantumFilm devices for near infrared sensing applications and will present a characterization of our devices. We demonstrate that QuantumFilm's global shutter operation offers a vehicle for achieving high-shutter-efficiency global shutter in 1.1 μm pixel CMOS image sensors.

10098-58, Session 14

Analysis of SiNx TIR mirror for polygonal ring resonator sensor structure

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In this paper, total internal reflection (TIR) mirror is carefully simulated for silicon nitride polygonal ring resonator sensor structure. Polygonal resonator does not have a bending loss, and it has an advantage of using MMI coupler. It has recently attracted many attentions for applications in bio and chemical sensors. In polygonal resonator sensor design, high Q-factor and low TIR mirror loss are extremely significant factors. Therefore, critical angle and Goos-Hanchen shift should be considered in the design of TIR mirror. When cladding material is SiO2, the critical angle of SiNx waveguide is about 45 degrees and the Goos-Hanchen shift is about 500 nm at 1.55 um wavelength. For a ridge type waveguide designed to have 3 um width, 1 um height, and 0.5 um etching depth for decreasing TIR mirror loss. As simulation results of FDTD, reflectivities of polygonal TIR mirrors are 29% for square, 79% for pentagon, 95% for hexagon and 98% for octagon, respectively. According to the simulations, Q-factors for hexagonal and octagonal resonators can be obtained as high as 1.55?10^4 and 1.72?10^4, respectively.

10098-59, Session 14

Strain sensor based on sectional crosstalk change in dual-core fibers

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Multi-core fibers are recognized as the medium designed to be used in telecommunication for space division multiplexing. At the same time, they can be advantageously used in sensor technology. The most crucial parameter for multi-core fibers is crosstalk, as its presence at a high level is found to be highly undesirable in telecommunication applications. However, this phenomenon can be used advantageously in the construction of new types of fiber optic sensor.

For the strain sensor, we used dual-core microstructured fiber. In the presented research, we take advantage of the technology of fiber post-processing, namely fiber tapering. This treatment, which enables changes in the conditions of interference between supermodes, makes the fiber sensitive to elongation. In the un-tapered section, supermodes do not interfere efficiently (crosstalk <-50dB), whereas in the tapered section the crosstalk increases significantly (crosstalk = 0dB meaning all the power from one core can be transferred to the neighbored core), creating a strain sensitive area. The distribution of power between the cores of a multi-core fiber at the output of the sample depends on the elongation of the sample. The strain value can be read off both in the domain of power and wavelength. Research results show that sensor performance can be adjusted by changing the taper length and ratio. The results presented are promising for the construction of a temperature independent strain sensor, whose strain sensitivity (17nm/m?) is far better than optical fiber sensors based on Fiber Bragg Gratings. Meanwhile, the temperature sensitivity is negligible assuring no cross-sensitivity.

10098-60, Session 14

Autofocus changes the paradigm for camera technology

Lisanne Glavin, PixeLINK (Canada)

Leveraging Varioptic electrowetting liquid lens technology, an autofocus camera delivers fast, noiseless, controllable autofocus from 10 cm to infinity. The Varioptic lens offers application-controlled and user programmable-controlled auto focus capabilities in board-level and enclosed PixeLINK cameras.

Here are the some of the applications that benefit from using the Auto Focus Lens:

1) PCB inspection

As PCBs become smaller, more complex, there is a growing need for auto focus.

Evaluation of component placement prior to reflow. Bare board and solder paste inspection.

Checking for open or short circuits.

2) Biometrics

Biometric applications require the ability to quickly autofocus on the target feature.

A growing number of airports are adding kiosks that perform facial recognition and compare it to a biometric passport.

3) Medical

Imaging of live cells, tissues and organisms benefits from autofocus by quickly being able to focus on specimens entering the field of view.

Autofocus can compensate for thermal drift or uneven culture dishes.

4) Parcel processing – inspection of bar codes

Required at most post offices and shipping companies for data collection and sorting.

Bar codes can be located on multiple sides of the package. Packages can be of varying sizes.

10098-68, Session 14

Modeling of frequency response in strain balanced SiGeSn/GeSn quantum well infrared photodetector

Prakash Pareek, Ravi Ranjan, Mukul Kumar Das, Indian School Of Mines (India)

In Recent times, Quantum well infrared photodetectors (QWIP) transform themselves into backbone of high speed communication systems. Recently, a lot of research is conducted towards realizing group IV based QWIP which are cheap as well as offer heterogeneous integration with CMOS technology on silicon substrate. Fortunately, alloying Germanium with ?-Sn(Tin) can effectively reduce the direct-bandgap of Germanium more than its indirect-bandgap and, hence, a direct-bandgap GeSn alloy can be realized. Moreover, spectral response of GeSn based detector covers infrared range of wavelength. Thus GeSn alloy can be used as an active layer in group IV QWIP. In case of group IV based QWIP, detailed physics related to carrier transport mechanism is still not clear understood unlike their III-V counterparts. In this work carrier transport mechanism in strain balanced SiGeSn/GeSn QWIP is studied to obtain the frequency response. A 76Å thick Ge0.83Sn0.17layer is sandwiched between two tensile strained Si0.09Ge0.8Sn0.11 layers to form a type-I single strain balanced quantum-well infrared photodetector (SQWIP). A fully relaxed Ge0.872 Sn0.128 layer is used as a buffer layer. The rate equation in quantum well and continuity equation over the well are solved simultaneously to obtain generated photocurrent. The effect of applied bias and thermionic emission rate on the frequency response is also presented and analyzed. The 3dB bandwidth is calculated for SQWIP is quite large (>500 GHz) due to direct band gap of active GeSn layer and single well structure. The results also show that thermionic emission deteriorates the frequency response but increase the bandwidth.

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10099-1, Session 1

Tandem solar cells with infrared-tuned silicon bottom cells *(Invited Paper)*

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We modify silicon heterojunction solar cells for the near-infrared (NIR) spectrum and reduced generation rate that they experience in tandems, with a focus on the front transparent conductive oxide layer and rear reflector. These cells are then incorporated into both two-terminal and four-terminal tandems, including a new, optically coupled tandem architecture that utilizes a silicon "PVMirror". A PVMirror is a curved PV module that may include a spectrum-splitting film or coating on the sunward side of the cells. Near-infrared light is transmitted to the silicon cells, whereas visible (and potentially infrared) light is reflected and focused—thanks to the curvature of the PVMirror—onto a second, complementary solar converter. Though there are many potential embodiments of the PVMirror technology, this talk presents initial results for a parabolic trough PVMirror incorporating silicon "bottom" cells with a GaAs receiver at its focus. Our best NIR-tuned silicon cells reach a peak spectral efficiency of 42% at 900 nm, and PVMirrors with these cells coupled with GaAs receivers demonstrate outdoor efficiencies of over 24% with respect to the global irradiance and over 28% with respect to the direct normal irradiance.

10099-2, Session 1

Double and triple junction Si tandem solar cells *(Invited Paper)*

Steven A. Ringel, Tyler J. Grassman, Daniel J. Chmielewski, The Ohio State Univ. (United States)

Silicon-based tandem solar cells are receiving vigorous attention in the photovoltaics (PV) field. The interest is being driven by two primary reasons. First are the recent advances in the ability to achieve high quality, epitaxially-integrated III-V compound semiconductors with Si through the careful mitigation of interface-driven defects such that nearly ideal bandgap profiles utilizing a bottom Si junction can be realized. The second reason is more economics-based, and is driven by the need to even further lower the $/Watt metric of Si PV systems, the analysis of which has led to a push for increasing Si cell efficiencies toward 30% or more while controlling costs. Such Si efficiencies can be achieved via the use of a Si tandem cell and here we present our recent work on both double junction tandems based on GaAs.75P.25/Si (1.7 eV/1.1 eV) and triple junction tandems based on Ga.57In.43P/GaAs.9P.1/Si (2.0 eV/1.54 eV/1.1 eV) materials and cells. By achieving these cells in a single, metal-organic chemical vapor deposition (MOCVD) growth run and process, the Si substrate serves a dual role as both an active solar cell and low cost growth substrate that is amenable to future industry transfer. Key to this effort is the use of a compositionally graded GaAsP buffer, grown directly on Si, serving as a semi-transparent integration layer such that the ideal bandgap profiles of the upper junctions can be achieved and fully integrated both optically and electrically with the underlying Si solar cells. With double junction Si tandem cells displaying open circuit voltages (Voc) greater than 1.6 V (20% efficiency prior to any optimization) and the very first triple junction Si tandems already displaying Voc values in excess of 2.6 V, these cells are opening up a new paradigm for achieving high efficiency Si-based cells in a process that has potential for insertion into existing manufacturing. Full details of the properties and performance of cells, their components such as metamorphic tunnel junctions, will be described.

10099-3, Session 1

GaSb on GaAs Solar Cells Grown using Interfacial Misfit Arrays

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State of the art InGaP2/GaAs/In0.28Ga0.72As inverted metamorphic (IMM) solar cells have achieved impressive results, however, the thick metamorphic buffer needed between the lattice matched GaAs and lattice mismatched InGaAs requires significant effort and time to grow and retains a fairly high defect density. One approach to this problem is to replace the bottom InGaAs junction with an Sb-based material such as 0.73 eV GaSb or ~1.0 eV Al0.2Ga0.8Sb. By using interfacial misfit (IMF) arrays, the high degree of strain (7.8%) between GaAs and GaSb can be relaxed solely by laterally propagating 90° misfit dislocations that are confined to the GaAs-GaSb interface layer.

We have used molecular beam epitaxy to grow GaSb single junction solar cells homoepitaxially on GaSb and heteroepitaxially on GaAs using IMF. Under 15-sun AM1.5 illumination, the control cell achieved 5% efficiency with a WOC of 366 mV, while the IMF cell was able to reach 2.1% with WOC of 546 mV. Shunting and high non-radiative dark current were main cause of FF and efficiency loss in the IMF devices. Threading dislocations or point defects were the expected source behind the losses, leading to minority carrier lifetimes less than 1ns. Deep level transient spectroscopy (DLTS) was used to search for defects electrically and two traps were found in IMF material that were not detected in the homoepitaxial GaSb device. One of these traps had a trap density of 7 ? 1015 cm-3, about one order of magnitude higher than the control cell defect at 4 ? 1016 cm-3.

10099-4, Session 1

Symmetric and asymmetric (Ga,In)(P,As,N) quantum well and superlattice solar cells for lattice matched III-V/Si tandems

Alexandre Freundlich, Khim Kharel, Univ. of Houston (United States)

Here we study photovoltaic properties of GaInPNAs based quantum well and superlattice solar cells that are strain balanced or lattice matched to Si and evaluate their potential toward the development of high efficiency tandems operating in conjunction with a silicon bottom cells.

10099-5, Session 2

Silicon-hybrid multi-junction devices for photovoltaic and (photo-)electrochemical applications *(Invited Paper)*

Hairen Tan, Technische Univ. Delft (Netherlands) and Univ. of Toronto (Canada); Johan Blanker, Paula Perez Rodriguez, Ravi Vasudevan, Michael Falkenberg, Technische Univ. Delft (Netherlands); Alice Furlan, Rene A. J. Janssen, Technische Univ. Eindhoven (Netherlands); Miro Zeman, Arno H. M. Smets, Technische Univ. Delft (Netherlands)

Photovoltaic (PV) device configurations based on multi-junctions have the advantage of improved utilization of both photons in the solar spectrum and the energy of the photons. Low-bandgap semiconductors in bottom PV junctions allow to efficiently utilize the low energetic photons, whereas high-bandgap semiconductors in the top PV junctions allow to efficiently utilize the photon energy for high voltage generation. Besides that multi-junctions PV devices are a straightforward approach to achieve higher solar-to-electricity conversion efficiencies (?), they are interesting building blocks for water splitting devices based on PV/photo-electrochemical(PEC) or PV/electrochemical(EC) configurations. Multi-junctions PV devices deliver high flexibility in delivering the combination of high voltages of 1.6-2.0 V required to split water combined and relatively high current densities.

Every type of multi-junction device configuration exhibits its own advantage, like high conversion efficiencies, cost-effective module topologies, limited usage of materials, easy up-scalable processing methods for large areas, high water resistant PV materials to allow flexible and cheaply encapsulated modules and high voltage (and current) material devices for monolithically integrated PEC-PV concepts.

The results of various types of devices will be presented: a-Si:H/nc-Si:H 2-junctions, a-Si:H/nc-Si:H/nc-Si:H 3-junctions, a-Si:H/CIGS 2-junctions, a-Si:H/OPV 2-junctions, and a-Si:H/a-Si:H/OPV 3-junctions, nc-Si:H/c-Si 2-junction and a-Si:H/nc-Si:H/c-Si 3-junction. The general design rules to accomplish high conversion efficiencies of these hybrid devices are discussed. Important aspects as current matching between the junctions; modulated surface textured substrates and interfaces to establish a compromise between ideal light trapping and processing of high quality PV materials; bi-functional intermediate layers that act as reflector layers and tunnel recombination junctions; and minimalizing the parasitic absorption losses of supporting layers will be discussed. Record efficiencies for PV devices based on a-Si:H/nc-Si:H (?initial=14.8%), a-Si:H/OPV (?initial=11.6%) and a-Si:H/a-Si:H/OPV (?initial=13.2%) will be reported. Preliminary results on a-Si:H/CIGS and a-Si:H/nc-Si:H/c-Si PV devices will be presented. The crucial design and processing steps for these devices to accomplish record efficiencies will be presented as well. Finally, examples of the integration of these multi-junction devices in PV/EC and PV/PEC devices will be presented.

10099-6, Session 2

CNT doped PEDOT:PSS / Silicon Hybrid Heterojunction Solar Cells

Yi-Chun Lai, National Chiao Tung Univ. (Taiwan); Chien-Chung Lin, National Chiao Tung Univ (Taiwan); Sih-Han Chen, Pei-Ting Tsai, Chu-Yen Hsiao, Li-Wei Zheng, Ruei-Ying Wu, Bun-Hua Huang, Gou-Chung Chi, Hsin-Fei Meng, Peichun Yu, National Chiao Tung Univ. (Taiwan)

In this work, highly transparent and conductive multi-wall- carbon nanotubes (MW-CNTs) are employed to realize solution-processed, hybrid silicon (Si) Schottky -junction solar cells. We first describe the optimization of device structures on silicon wafers with nanowire and micro-pyramidal surface textures, and compare the device characteristics with those of hybrid cells based on Si and poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS). The optimized processing conditions include the length of silicon nanowires, the annealing temperature, and the shading ratio of the frontal silver grids. It is found that the hybrid CNT cells outperform the hybrid PEDOT:PSS counterpart under individually optimized processing conditions due to better transparency and conductivity of CNTs than PEDOT:PSS. The best hybrid CNT cells, fabricated using a 14% grid shield ratio, 150 °C annealing temperature, and 150nm nanowire length, achieve a PCE of 11.90% and 13.82% in micro-pyramid and nanowire (NW) textured silicon, respectively, in contrast to 7.43% and 12.96% for hybrid PEDOT:PSS cells. To control the rear surface recombination, we further employ two solution-processed, small-molecule materials, Tris(8-hydroxyquinolinato) aluminium (Alq3) and 1,3-bis(2-(4-tert-butylphenyl)-1,3,4-oxadiazol-5-yl) benzene (OXD-7) via a blade-coating technique between the silicon wafer and aluminum electrode. As a result, the PCE of hybrid CNT/Si NW solar cells is enhanced to 13.92% and 14.41% with the insertion of the Alq3 and OXD-7 rear interlayer, respectively. With the high power conversion efficiency (PCE), manufacturing Si-based solar cells at temperatures below 150 °C without high vacuum conditions not only significantly lowers the fabrication cost, but also enables the use of ultrathin substrates to save on the material cost for the future.

10099-7, Session 2

20-junction photonic power converter performance under non-uniform illumination calculated by 3D distributed circuit model

Sanmeet Chahal, Mathew M. Wilkins, Univ. of Ottawa (Canada); Denis P. Masson, Simon Fafard, Azastra Opto Inc. (Canada); Christopher E. Valdivia, Karin Hinzer, Univ. of Ottawa (Canada)

Distributed circuit models (DCM) divide photovoltaic devices into discrete elementary units. Each unit is assigned an equivalent circuit based on geometry and location, with circuit parameters being fit to or extrapolated from experimental results. Interconnection of these elementary units with ohmic resistors representing lateral and vertical resistances within the layers of the device forms the complete circuit model. DCMs allow grid design optimization, simulation of chromatic aberration, luminescent coupling and analysis of power losses due to regionally specific resistances, which are not possible with simple lumped models. Previous DCMs have been limited to 1-3 junction devices, using a 2D surface model, or use of a one-diode circuit model for the cell junctions. Furthermore, a DCM can be used to simulate complex multi-junction devices with non-uniform illumination, whereas in comprehensive physics-based simulators like Synopsys TCAD Sentaurus this would require vastly greater computational resources.

In this work, a parameterized 3D distributed circuit model was developed to calculate the performance of III-V solar cells and photonic power converters (PPC) with a variable number of epitaxially stacked pn junctions. We validated these calculations against published results using a similar 3D model for a 1-junction solar cell. Furthermore, experimental results from Azastra Opto's 20-junction PPC illuminated by an 845 nm diode laser are compared. These devices are designed with many pn junctions to achieve higher voltages and to operate under non-uniform illumination profiles from a laser or LED. The effect on device performance of varying both these parameters will be discussed.

10099-8, Session 2

Practical considerations for solar energy thermally enhanced photo-luminescence devices

Nimrod Kruger, Assaf Manor, Matej Kurtulik, Tamilarasan Sabapathy, Carmel Rotschild, Technion-Israel Institute of Technology (Israel)

While single-junction photovoltaics (PV's) are considered limited in conversion efficiency according to the Shockley-Queisser limit, concepts such as solar thermo-photovoltaics aim to harness lost heat and overcome this barrier. We claim the novel concept of Thermally Enhanced Photoluminescence (TEPL) as an easier route to achieve this goal.

Here we present a practical TEPL device where a thermally insulated photo-luminescent (PL) absorber, acts as a mediator between a photovoltaic cell and the sun. This high temperature absorber emits blue-shifted PL

at constant flux, then coupled to a high band gap PV cell. This scheme promotes PV conversion efficiencies, under ideal conditions, higher than 62% at temperatures lower than 1300K. Moreover, for a PV and absorber band-gaps of 1.45eV (GaAs PV's) and 1.1eV respectively, under practical conditions, solar concentration of 1000 suns, and moderate thermal insulation; the conversion efficiencies potentially exceed 46%.

Some of these practical conditions belong to the realm of optical design; including high photon recycling (PR) and absorber external quantum efficiency (EQE). High EQE values, a product of the internal QE of the active PL materials and the extraction efficiency of each photon (determined by the absorber geometry and interfaces), have successfully been reached by experts in laser cooling technology. PR is the part of emitted low energy photons (in relation to the PV band-gap) that are reabsorbed and consequently reemitted with above band-gap energies. PV back-reflector reflectivity, also successfully achieved by those who design the cutting edge high efficiency PV cells, plays a major role here.

10099-9, Session 2

Spectral and angular-selective thermal emission from gallium-doped zinc oxide thin film structures

Enas Sakr, Peter Bermel, Purdue Univ. (United States)

Simultaneously controlling both the spectral and angular emission of thermal photons can qualitatively change the nature of thermal radiation, and offers a great potential to improve a broad range of applications, including infrared light sources and thermophotovoltaic (TPV) conversion of waste heat to electricity. For TPV in particular, frequency-selective emission is necessary for spectral matching with a photovoltaic converter, while directional emission is needed to maximize the fraction of emission reaching the receiver at large separation distances. This can allow the photovoltaics to be moved outside vacuum encapsulation. In this work, we demonstrate both directionally and spectrally-selective thermal emission for p-polarization, using a combination of an epsilon-near-zero (ENZ) thin film backed by a metal reflector, a high contrast grating, and an omnidirectional mirror. Gallium-doped zinc oxide is selected as an ENZ material, with cross-over frequency in the near-infrared. The proposed structure relies on coupling guided modes (instead of plasmonic modes) to the ENZ thin film using the high contrast grating. The angular width is thus controlled by the choice of grating period. Other off-directional modes are then filtered out using the omnidirectional mirror, thus enhancing frequency selectivity. Our emitter design maintains both a high view factor and high frequency selectivity, leading to a factor of 20 enhancement over a typical blackbody emitter, through a combination of a 43% increase in view factor and a 14x enhancement in frequency selectivity. This calculation assumes a Si PV converter five widths away from the same width emitter in 2D at 1573 K.

10099-10, Session 3

Device physics of Cu(In,Ga)Se2 solar cells for long-term operation *(Invited Paper)*

Jiro Nishinaga, Hajime Shibata, National Institute of Advanced Industrial Science and Technology (Japan)

The chalcopyrite compound Cu(In,Ga)Se2 (CIGS) has potential to be used as a semiconductor material for thin-film photovoltaic devices because of its high absorption coefficient and appropriate band gap, and CIGS solar cells have recently shown a record conversion efficiency of over 22%. However, there have been few reports investigating the long-term stability of CIGS solar cells compared with Si solar cells, and long-term operation for 20 years more is considered to be essential for decreasing the cost of solar cells. Therefore, the investigation of all degradation mechanisms is extremely important to promote CIGS solar cells. In this study, we investigate the degradation mechanisms of CIGS solar cells with air exposure, and discuss device physics of deteriorated solar cells and methods of recovering cell performance.

After damp heat testing, some CIGS solar cells show low shunt resistance and conversion efficiency, because low resistive layers are formed on the side edges of the solar cells. After removing the low resistive layers by alkaline solution etching, the conversion efficiency is completely recovered. The layers on the sidewalls are identified to be molybdenum oxides and sodium molybdate by Auger electron spectroscopy. Na, In, and Ga oxides on the sidewalls may act as recombination centers, and the saturation current density and ideality factor are confirmed to be improved after etching the oxides on the sidewalls. Diode parameters and fill factors (FF) are important for high-performance solar cells, and we discuss a bottleneck of high conversion efficiency for CIGS solar cells.

10099-11, Session 3

Relationship between microscale photophysics and structure in metal halide perovskite solar cells *(Invited Paper)*

Samuel D. Stranks, Cavendish Lab., Univ. of Cambridge (United Kingdom)

Metal halide perovskites such as CH3NH3PbI3 are highly promising materials for solar cells, with certified power conversion efficiencies already exceeding 22%. A key enabling property of the perovskites for photovoltaics is their high photoluminescence quantum efficiency, suggesting that these materials could in principle approach the thermodynamic device efficiency limits in which all recombination is radiative. However, recent reports have demonstrated the presence of non-radiative recombination sites which vary heterogeneously from grain to grain and limit performance.

Here, I will present results towards understanding the origin of this heterogeneity and non-radiative decay, and how this understanding can reveal pathways to eliminate these parasitic losses. Specifically, we assess the impact of local variations in structure on the local photophysical properties of high quality neat CH3NH3PbI3 perovskite films. We use time-resolved confocal photoluminescence (PL) measurements to map the local variations in emission intensities across the grains and grain boundaries. We then correlate these variations in emission with local variations in crystallinity and stress by utilizing the X-Ray micro-diffraction beamline at the Advanced Light Source facility. Our results reveal substantial variations in local structure, morphology and chemistry which correlate with the variations in local PL emission and lifetime. Our work highlights the intimate relationship between structure and optoelectronic behavior, and suggests that controlling local structure is crucial for minimizing non-radiative decay and ultimately reaching device efficiency limits.

10099-12, Session 3

(110) cubic and (100) rhombohedral Ge crystal formation on glass using Al-induced crystallization

Kaveh Shervin, Khim Kharel, Alexandre Freundlich, Univ. of Houston (United States)

Ge as a low bandgap material lattice matched with GaAs has been substantially a viable ?substrate ?for high efficiency multi junction solar cells. Costly Ge substrates have accelerated the ?need for ?the fabrication of highly orientation-controlled Ge films on inexpensive substrates. In ?the ?literature, Al induced crystallization (AIC) method has registered promising results on the ?formation ?of (111) dominated large grain size (>10 microns) polycrystalline Ge on glass.?

In this work, we have experimentally looked into the physics of low temperature ??(<400C) ?amorphous Ge crystallization using AIC favoring the formation of highly oriented ?large grain Ge ?crystals towards (110) or (100) suitable for solar cell applications. ?We have carefully investigated ?the effects of experimental parameters such as Al and Ge layers

?thicknesses, interfacial oxide ?layer (between Al and Ge layers) and annealing conditions on defining the Ge dominant ?orientation other ?than normally achieved (111). We have implemented X-Ray diffraction analysis ?to demonstrate ?the critical role of oxide layer in reducing the surface free energy. We have ?studied the playing ?role of Al thickness on tuning Ge dominant orientation and ?subsequently ?achieved (110)-oriented cubic Ge on glass, which could be particularly attractive to mitigate ?antiphase defect formation during the ? III-V heteroepitaxy. The optoelectronic properties of the ?films? have been investigated using ?Photo Luminance approach to ?measure poly-Ge band gap. ?Furthermore, we ?show for the first time the possibility of ?obtaining a? novel ?rhombohedric ??(100) ?Ge presenting ?a remarkable option toward ?tuning of the Ge ?lattice constant to ~0.593 nm ??(instead of 0.565nm), ?closely matched ?to the lattice of InP and related materials.?? ??

10099-13, Session 3

The role of N-H complexes in the control of intrinsic isoelectronic center recombination in hydrogenated GaInNAs

Vincent R. Whiteside, Miwa Fukuda, Nicholas J. Estes, Bin Wang, Collin R. Brown, The Univ. of Oklahoma (United States); Khalid Hossain, Terry D. Golding, Amethyst Research Inc. (United States); Mathieu Leroux, Mohamed Al Khalfioui, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France); Joseph G. Tischler, Chase T. Ellis, Evan R. Glaser, U.S. Naval Research Lab. (United States); Ian R. Sellers, The Univ. of Oklahoma (United States)

A significant improvement in the quality of dilute nitrides has recently led to the ability to reveal depletion widths in excess of 1 ?m at 1 eV [1]. The real viability of dilute nitrides for PV has been recently demonstrated with the reporting of a record efficiency of 43.5% from a 4J MJSC including GaInNAs(Sb) [2]. Despite the progress made, these materials remain poorly understood and work continues to improve their lifetime and reproducibility.

We have investigated the possibility of improving the functionality of GaInNAs using hydrogenation to selectively passivate mid-gap defects, while preserving the substitutional nitrogen. Temperature dependent photoluminescence measurements of the intrinsic region of a GaInNAs p-i-n solar cell show a classic "s-shape" associated with localization prior to hydrogenation. No sign of this "s-shape" is evident after hydrogenation, despite the retention of substitutional nitrogen as evidenced by the band absorption of 1 eV. The absence of an "s-shape" at low-temperature in hydrogenated GaInNAs is rather curious since, even in high quality nitrides this behavior is due to the emission of isoelectronic centers created via N-As substitution [3]. The potential origins of this behavior will be discussed. The promise of this process for GaInNAs solar cells was demonstrated by a three-fold improvement in the performance of a hydrogenated device with respect to an as-grown reference [4].

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10099-14, Session 4

Properties of dilute nitride pseudo-alloys grown using a nitrogen delta-doping technique *(Invited Paper)*

Shuhei Yagi, Saitama Univ. (Japan); Yoshitaka Okada, The Univ. of Tokyo (Japan); Hiroyuki Yaguchi, Saitama Univ. (Japan)

A small amount of nitrogen addition into (In)GaAs has strong impacts on its lattice parameters, optical, and electronic properties. We have investigated nitrogen containing alloys grown by molecular beam epitaxy using a nitrogen delta-doping technique targeted for novel solar cell applications. Nitrogen induced splitting of the conduction band into two subbands makes it possible to use as an intermediate-band material. We found that periodic insertion of nitrogen delta-doped layers into GaAs with nanometer-scale periods enhances optical transitions related to the upper conduction subbands compared with those observed in conventional GaAsN random alloys, and thus proposed such GaAs:N delta-doped superlattices (SLs), or pseudo-alloys, as superior candidates for the absorber of high-efficiency intermediate-band solar cells (IBSCs). Here, we discuss the potential of this material system through our recent results on the IBSCs with a SL absorber. Another important application of dilute nitride semiconductors is to use them in lattice-matched 4-junction tandem solar cells. Simultaneous incorporation of In and N in GaAs reduces the fundamental gap while keeping the lattice constant. The growth of the InGaAsN quaternary system via the nitrogen delta-doping technique enables us to control the spatial configuration of the constituent atoms in the matrix. The effect of bonding configurations in InGaAsN pseudo-alloys of which the lattice constant matches to GaAs and Ge on the optical and electronic properties will be shown and discussed.

10099-15, Session 4

Photon upconversion using InAs-based quantum structures and the control of intermediate states *(Invited Paper)*

Itaru Kamiya, Toyota Technological Institute (Japan); David M. Tex, Kyoto Univ. (Japan); Yuwei Zhang, Toyota Technological Institute (Japan); Yoshihiko Kanemitsu, Kyoto Univ. (Japan)

We have reported that a novel quantum structure which we term quantum well island (QWI), a few monolayer thick and sub-micron wide structure, is effective in confining the carriers and enhancing multi-exciton interactions. By embedding InAs-based QWIs in AlGaAs barrier layers, we demonstrated that upconverted photoluminescence (PL) in the visible regime can be obtained by impinging near infrared (IR) photons, which may potentially be applied for intermediate band (IB) solar cells [1]. Further investigation has revealed that the dominant upconversion mechanism is most likely Auger, while two-step excitation may also take place under selected conditions [2]. The upconverted carriers generated by IR irradiation may also be detected as photocurrents. Through a series of studies using this structure, we note the importance of the carrier trapping involved during the upconversion processes. For instance, multiple laser-beam excitation measurements have shown that trapping and re-trapping processes reduce the photocurrents [3].

However, recently, using a structure that consists of InAs quantum dots embedded in InAs/GaAs multi-quantum wells (MQWs), we find that efficient carrier trapping can enhance upconverted PL [4]. We show the preparation and the control of this structure by molecular beam epitaxy (MBE), and the possible mechanisms of the upconversion. We also discuss how the conversion efficiency may be improved using device structures based on this concept.

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10099-16, Session 4

Influence of Si doping on InAs/GaAs quantum dot solar cells with AlAs cap layers

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Intermediate band solar cells (IBSCs) have the potential to exceed the Shockley-Queisser limit and attain efficiency up to 63 %. One of the requirements for strong sub-bandgap photon absorption in the quantum dot intermediate band solar cell (QD-IBSC) is the partial filling of the intermediate band (IB). Studies have shown that the partial filling of the intermediate band can be achieved by introducing Si doping to the quantum dots. However, the existence of excessive Si dopants has shown to cause the formation of point defects, and hence the reduction of photocurrent.

In this work, Si doping in InAs/GaAs QDSCs with AlAs cap layers (CLs) for (i) saturation of strain-induced dislocations and (ii) QD state filling is demonstrated. Previously, we have reported that the deposition of AlAs CLs on InAs QDs could suppress the formation of the WL. As a result of the WL removal, the effective bandgap of the QDSC could be increased, which in turn led to the increase in the thermal activation energy and the open-circuit voltage. In this study, we demonstrate an additional enhancement of the VOC by ~ 44 mV by defect state passivation via moderate level of Si doping (6 e/dot) in InAs/GaAs QDSCs with AlAs CLs. The moderate Si doping led to an enhancement of the carrier lifetime in the QDs, and hence the VOC. Furthermore, the QD state filling, which is essential for strong two-photon absorption, is observed with significantly lower Si doping densities when compared with that of our previous study.

10099-17, Session 4

Multiband modification of III-V dilute nitrides for IBSC application

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In an intermediate band solar cell (IBSC), the presence of IB electron escape pathways either by direct tunneling or/and by the thermal excitation can reduce the IB occupation as well as the photocurrent production by the two-step photon absorption (TSPA) process. Modification of the sub-bandgaps (E- and E+) in the conduction band (CB) in GaNAs highly mismatched alloys by varying the N content can provide means to control the thermal escape path of IB electrons at E- over an electron-barrier layer in an IBSC device. A set of GaNAs IBSC structures with different N content (up to 2.1%) were studied. A reactive N flux was generated by using a radio-frequency (RF)-plasma source in the molecular beam epitaxy chamber, and N contents in the GaAs host was controlled by adjusting the RF-plasma power. A chopped IR light source with wavelengths longer than 1400 nm was used for TSPA measurements. An improvement in the TSPA-induced photocurrent was observed for devices with high N contents. These data indicate the improved photo-assisted collection by the IR light relevant to the IB-CB bandgap. The high IR-photon collection would mean a low thermal escape of the IB electrons as well as high IB occupation. An opposite trend was observed in external quantum efficiency (EQE) experiments at the IB-CB bandgap regime, namely low EQE signals for the high-N devices. Such behaviors confirm that the high TSPA signals are due to the low level thermal escape of IB electrons compared to that in the low-N device.

10099-18, Session 5

The potential of type-II quantum dots and quantum wells for third-generation photovoltaics *(Invited Paper)*

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Third generation photovoltaics aims to improve the efficiency of solar cell technology while keeping costs below levels that are prohibitive for practical implementation. The major loss processes in commercial solar cells include high-energy thermal losses and transmission of low energy photons that cannot be harnessed by conventional single-gap solar cells. Quantum-engineered systems have long been considered an exciting route to enhance the performance of traditional solar cells via: the absorption of low energy photons in intermediate band solar cells (IBSCs), or the extraction of high-energy photogenerated carriers extracted prior to thermalization using a combination of hot carrier absorbers (HCAs) and energy selective contacts. Several systems have been investigated for IBSCs and HCAs the majority of which utilize type-I quantum dots and quantum wells. Although there is some work on type-II structures these systems are much less developed. These structures have several advantages over conventional type-I systems, which will be discussed, and prove particularly interesting for studies of HCAs and quantum dot (QD) IBSCs. Two specific systems will be presented: 1, InAs/GaAs1-xSbx QD IBSCs [1, 2]; and 2, Type-II InAs/AlAsSb quantum wells for HCAs [3, 4]. Sb-capped QDs have demonstrated several interesting properties including: non-conventional current-voltage properties, and evidence of competing tunneling and thermal processes that dominate the carrier escape and transport. Experimental investigations of HCAs based on InAs/AlAs1-xSbx quantum wells have displayed evidence of robust hot carrier populations at elevated temperatures where phonon relaxation is expected to dominate.

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10099-19, Session 5

Uncovering hot carrier cooling mechanisms in multiple quantum wells

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The Hot Carrier solar cell has the potential to yield a very high efficiency, well over 50% under 1 sun. Multiple quantum wells have been shown to have significantly slower hot carrier cooling rates than bulk material [Hirst et al,

Rosenwaks et al] and are thus a promising candidate for hot carrier solar cell absorbers. However, the mechanism(s) by which hot carrier cooling is restricted is not clear.

Results will be presented from a systematic study of carrier cooling rates in GaAs/AlAs MQW with either varying barrier or with varying well thickness. These allow a determination as to whether the mechanisms of either a reduction in hot carrier diffusion; a localisation of phonons emitted by hot carriers; or mini-gaps in the MQW phonon dispersion are responsible for these reduced carrier cooling rates.

Initial time resolved PL measurements at high carrier densities show that the photoluminescence spectra evolve over several nanoseconds. Indicating that the electronic state occupation varies slowly after laser pulse excitation. This is indicative of either slow carrier cooling, state filling, or a combination of both of these effects.

Results will be placed in the context of use of MQW as absorbers in a real hot carrier cell.

10099-20, Session 5

Optical characterization and electrical control of charge carrier populations in a quantum-well hot carrier solar cell

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We report on the optoelectronic characterization of quantum-well solar cells presenting a power conversion efficiency of 11% under laser illumination equivalent to 15 000 Suns. Short-circuit current is proportional to laser power in the entire range, showing an excellent carrier generation and collection. Open-circuit voltage surpasses the quantum well's lowest interband transition energy, suggesting a nonlinear working regime. To study the link between the cell's performance and the thermodynamics of photo-generated carriers, photoluminescence spectra are fitted using the generalized Planck's law. The energy-dependent absorptivity, which must be identified to obtain good fit accuracy, takes into account the absorption of excitons and free carriers in the quantum well. Furthermore, electrical injection and extraction across the barriers modify the temperature of the quantum well's carrier population linearly, hinting at the role of barriers as semi-selective high-energy contact.

10099-21, Session 5

Novel metallic absorbers for hot carrier generation

Jeremy N. Munday, Univ. of Maryland, College Park (United States)

Nanostructuring of thin metallic films can lead to either resonant or broadband absorption depending upon design. Typically, such films and nanostructures lead to hot carrier generation followed by ohmic loss, resulting in dissipation of energy as heat. However, if the absorption occurs near an interface, an opportunity arises to capture the energy prior to electron thermalization. In this talk, we will present our recent work on hot carrier generation and collection in metallic films and nanostructures [1,2] and discussion future applications that could enable solar cells with efficiencies in excess of 40%, without optical concentration [3]. We will show fabricated hot carrier devices use CMOS compatible metals [2], e.g. Al, and designs for novel metal alloys, discussing opportunities enabled by modifying the electron density of states as well as the optical properties [4]. Applications to both improved photovoltaic performance and near-IR detectors will be presented.

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10099-22, Session 5

Modeling and characterization of double resonant tunneling diodes for application as energy selective contacts in hot carrier solar cells

Zacharie Jehl, Anatole Julian, The Univ. of Tokyo (Japan); Cyril Bernard, The University of Tokyo/NextPV (Japan); Naoya Miyashita, The Univ. of Tokyo (Japan); Francois Gibelli, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); Yoshitaka Okada, The Univ. of Tokyo (Japan); Jean-Francois Guillemolles, The Univ. of Tokyo (Japan) and Institut de Recherchet et Developpement sur l'Energie Photovoltaique (France)

The realization of energy selective contacts is a cornerstone in the development of hot carrier solar cells, yet remains a scientific lock preventing the realization of a proof of concept devices. In this work, we use double resonant tunneling barriers to achieve energy filtering, which implies that the energy position and electronic transmission width should be finely tuned. From a numerical model based on the transfer matrix approach, it was observed that the symmetry breaking resulting from the application of an electric bias on the structure greatly reduces the electronic transmission of the double barriers, hence the conductivity of the selective contact. However, the modeling of asymmetric double barriers showed a significant increase of the tunneling current, calculated using the Esaki-Tsu formula from the electronic transmission, owing to the compensation of the symmetry breaking by the asymmetry of the barriers. Using molecular beam epitaxy, we realized symmetric and asymmetric double barriers which were characterized by temperature dependent current-voltage analysis. Similarly to what was observed in the simulations, a significantly better tunneling current was observed from the negative differential resistance peak in the asymmetric double barriers samples, especially at room temperature where solar cells are supposed to operate. Moreover, by fitting the current-voltage curves, an experimental value for the double barrier transmission was obtained, bringing valuable information such as the extraction energy level, energy width as well as the experimental value of the Seebeck coefficient for the double barrier, giving a direct measurement of the expected voltage gain from the double barrier used as energy selective contact in a hot carrier solar cell.

10099-23, Session 6

Surface analysis of chalcogenide semiconductors used in photovoltaics *(Invited Paper)*

Angus A. Rockett, Colorado School of Mines (United States)

Both CdTe and Cu(In,Ga)Se2 have produced highly efficient thin film solar cells, exceeding 22% in champion devices. Both are also manufactured in large scales and show promise as future energy technologies. However, understanding the current collection mechanisms and mechanisms of instability in the devices remain a concern. To address these questions, we

have used scanning probe and photoemission spectroscopies to study the response of chalcogenide materials to light and how charge is collected. Results of scanning microwave impedance microscopy and conductive atomic force microscopy show dramatic differences in the behavior of CdTe and Cu(In,Ga)Se2 (CIGS). The results include characterization of the effect of CdCl2 treatment on the properties CdTe grains and grain boundaries. This treatment dramatically increases the current collection in the grain boundaries. Thus we show that CdTe solar cells operate apparently by generation of electron hole pairs in the CdTe grains and collection of electrons to the grain boundaries. By contrast, CIGS grains show little or no contrast between the grains and grain boundaries and no obvious conduction pathway through the grain boundaries appears to exist. Our surface analysis results are supplemented with other measurements of both surface and bulk microchemistry and microstructure.

10099-24, Session 6

Perovskite solar cells: functionality at the nanoscale *(Invited Paper)*

Joseph L. Garrett, Elizabeth Tennyson, Jeremy N. Munday, Marina S. Leite, Univ. of Maryland, College Park (United States)

Today, the best perovskite solar cells have power conversion efficiency > 21%, comparable to CdTe and CIGS polycrystalline devices. Nevertheless, the wide implementation of this emerging material as a reliable PV technology requires the control of device degradation that takes place during the solar cell operation. In order to advance the understanding of why and how the perovskites degrade so quickly when exposed to light and high relative humidity, we combine a set of scanning probe microscopy methods to determine the local variations of open-circuit voltage (Voc) and short-circuit current (Jsc) with nanoscale spatial resolution. We use a variant of Kelvin-probe force microscopy to map, in real-time, the transient behavior of the Voc in perovskite solar cells with spatial resolution < 50 nm. By performing 16 seconds/frame scans we resolve the role of humidity on the voltage degradation of the devices while mimicking 1-sun operation conditions. In a low humidity environment we measure local variations in Voc > 300 mV, resulting from ion migration. We probe the effect of light-induced reaction by spectrally dependent scanning photocurrent microscopy.

10099-25, Session 6

Exploiting absorption-induced self-heating in solar cells

Sascha Ullbrich, Axel Fischer, Enkhtur Erdenebileg, Christian Koerner, Sebastian Reineke, TU Dresden (Germany); Karl Leo, IAPP, Dresden University of Technology (Germany); Koen Vandewal, TU Dresden (Germany)

Absorption of light inevitably leads to a self-heating of each type of solar cell, either due to the excess energy of absorbed photons or non-radiative recombination of charge carriers. Although the effect of temperature on solar cell parameters such as the open-circuit voltage are well known, it is often ignored in Suns-Voc measurements [1]. This measurement technique enables direct access to the diode ideality factor without an influence by series resistance. A frequently seen decrease of the ideality factor or a saturation of the open-circuit voltage at high illumination intensities is often attributed solely to surface recombination [2], the shape of the density of states (DOS) [3], or the quality of the back contact in inorganic solar cells [4]. In this work, we present an analytical model for taking into account absorption induced self-heating in Suns-Voc measurements and validate it for various solar cell technologies such as small molecule organic solar cells, perovskite solar cells, and inorganic solar cells. Furthermore, with an adapted Suns-Voc technique, we are able to not only correctly determine the ideality factor, but also the relevant energy gap of the solar cell, which is especially of interest in the field of novel solar cell technologies.

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10099-26, Session 6

Investigation of carrier transport in CuInGaSe2 by highly spatially, spectrally, and time-resolved cathodoluminescence microscopy

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CuInGaSe2 (CIGSe) is a heavily disordered material. The temperature dependence of the diffusion length of excess carriers together with their lifetime gives access to the temperature dependence of the carrier mobility yielding information about the underling scattering mechanisms in the material.

Cathodoluminescence (CL) measurements have been performed on polycrystalline CIGSe, grown on Mo-coated soda lime glass in a single-stage-process and neither a buffer layer nor a window layer were applied. Absorbers with varying Cu/III-ratios (CGI: 0.73 and 0.9) and therefore varying grades of disorder were investigated.

The CIGSe backside was covered with 320 nm thick rectangular Ti-masks that allow CL excitation with electrons through this masks while completely absorbing the emerging luminescence from the underlaying CIGSe. Spectrally resolved CL-linescans perpendicular to the mask's edge as well as the undisturbed time resolved transients on the unmasked areas of the identical sample structure were recorded. The temperature dependence (4.5 K – 300 K) of both, lifetime as well as diffusion length, is determined and gives access to the temperature dependent mobility.

With decreasing temperature from 300 K to 4.5 K the diffusion length increases from 6 μm to 21 μm (CGI 0.9) and 23 μm (CGI 0.73) while the carrier lifetime increases from 22 ns (@125 K) to 48 ns (@4.5 K) and from 3 ns (@125 K) to 37 ns (@4.5 K), respectively. This results in an increase of the mobility with decreasing temperature, reaching up to 240,000 cm?/Vs and 340,000 cm?/Vs at 4.5 K.

10099-27, Session 7

Further improvement of the absorption efficiency of conventional vertical nanowires by tilting them

Mahtab Aghaeipour Kolyani, Mats-Erik Pistol, Lund Univ. (Sweden)

Over the last two decades there has been a dramatic increase in research activities related to nanowires (NWs) due to their exciting prospects for implementation of novel high-performance transistors, LEDs, lasers, photodetectors and sensors compatible with main-stream silicon technology. The geometry of NW devices plays a crucial role in many photonic applications e.g. photodetectors and solar cells where strong absorption resonances can be obtained by proper tailoring of NW diameter, length and pitch. Such enhancement of the light absorption is however typically accompanied by undesired resonance dips at specific wavelengths due to the cylindrical symmetry of the NWs. In this work, we theoretically study the absorption spectra of inclined InP NWs as a function of inclination angle and other relevant geometrical parameters by sophisticated electromagnetic modeling. In particular, we show that for an optimum inclination angle the broken symmetry of the system leads to excitation of other modes in the NWs which strongly reduces the dips in the absorption spectra leading to a significantly enhanced absorption compared to conventional vertically standing NWs. Interestingly, this improvement matches spectrally the intensity distribution of the sun, wherefore our results are expected to be important for NW-based photovoltaic applications. Although this work focuses on inclined InP nanowires, we believe that the results are of general interest regardless of the constituent material.

10099-28, Session 7

Microlens-based light-trapping enhancement in perovskite solar cells

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Perovskite solar cells have attracted wide interest of photovoltaic community due to their rapidly increasing efficiency from ~5% in 2012 to >21% in 2016. Although the perovskite material has very high absorption coefficient and solar cells made of thin layers ~300-400 nm absorb light brilliantly, there is still considerable loss in light absorption at ~440-480 nm, ~600-660 nm, and near the band edge ~700-800 nm.

To increase broad-band light absorption, we rigorously design experimentally realizable solar cell architectures with a microlens array using scattering-matrix simulations. Our simulations utilize commonly studied n-i-p device architecture with glass/ FTO/ TiO_2/ $CH_3NH_3PbI_3$/ Spiro:MeOTAD/ Gold. The microlens array is coupled to the air-glass side of the solar cell from where the light is incident. The microlens focuses light in the absorber layer that leads to increase in absorption and enhancement in photocurrent.

Our optimal architecture has a period of ~700 nm and microlens height of ~800-1000 nm with absorption and photocurrent enhancement of ~6.5% and 6% respectively, for nearly lossless metal cathodes. We also investigate the effect of perovskite layer thickness on the change in photocurrent and find that the photocurrent does not change much for thicknesses >400 nm.

The idea of integrating the microlens array with perovskite solar cell is particularly amenable for fabrication since it does not involve altering the internal solar cell structure which might affect the electron-hole transport adversely. These results could provide pathway to increasing the power conversion efficiency of state-of-the-art perovskite solar cells by >5%.

10099-29, Session 7

Plasmonic quantum-dot solar concentrator

Subhash Chandra, Trinity College (Ireland); Hind Ahmed, Trinity College Dublin (Ireland)

The Quantum Dot Solar Concentrator (QDSCs) device efficiency is undermined by re-absorption due to overlap of absorption and emission spectra of quantum dots, escape cone losses, and scattering losses at higher concentrations quantum dots. These losses could be significantly reduced if it were possible to guide quantum dots emission directionally and decrease the quantum dots concentration without compromising the total emission in device. The plasmonic coupling modulated optical properties of quantum dots employed to minimize losses and directionally guiding quantum dots emission in QDSCs device, it called Plasmonic Quantum Dot Solar Concentrator (PQDSCs). The anisotropic plasmonic coupling between quantum dots and gold nanorods is exploited to enhance quantum dots emission and simultaneously directionally guided. The nano-composite of gold nanorods and quantum dots were prepared in epoxy resin polymer as matrix medium. Subsequently, an external electric field was applied to manipulate the orientation of gold nanorods, hence the anisotropic plasmonic coupling. The plasmonic coupling parameters of spacing was controlled through concentration distribution of both quantum dots and gold nanorods. Finite Difference Time Domain (FDTD) modelling employed to theoretically predicted results of proposed plasmonic configuration and were compared against experimental to optimized plasmonic configuration for PQDSCs device. The results have shown significant enhancement in absorption, fluorescence emission, and directional emission of quantum dots in PQDSCs device.

10099-30, Session 7

Back surface patterning for enhanced absorption in epitaxial lift-off quantum-dot solar cells

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Quantum dots (QDs) can be used to engineer the bandgap of the middle junction in a tandem solar cell configuration to facilitate current matching. Furthermore, QDs are an avenue to the intermediate band solar cell (IBSC), which could exceed conventional limits of single junction cells with a theoretical maximum efficiency of 44.5%. However due to low surface coverage, hundreds of QD periods would be needed for an IBSC. This would pose significant challenges regarding growth time and strain balancing.

A feasible alternative to increase absorption in the QD region of the cell is light trapping. An epitaxial lift off (ELO) technique permits access to the back of the thin cell in order to utilize effective light trapping structures. Using a rear texture to randomize the angles of reflected light increases the proportion of light that is totally internally reflected and increases the optical path length.

This study compares four different back surface reflectors (BSRs) on quantum dot solar cell performance: a flat mirror, a one-dimensional (1-D) periodic texture with triangular features, a 1-D periodic texture with hemispherical features, and a 2-D pattern created with hexagonally close-packed spheres. A preliminary set of devices compared a rear mirror to the triangular BSR. The integrated external quantum efficiency (EQE) above 880 nm was 0.38 mA/cm2 for the mirror and 0.57 mA/cm2 for the triangular BSR, which represents a 30% increase in current. EQE and AM0 illuminated current-voltage results from the complete set of devices will be presented at the conference.

10099-31, Session 8

Photovoltaic reciprocity and quasi-Fermi level splitting in nanostructure-based solar cells *(Invited Paper)*

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The photovoltaic reciprocity theory relates the electroluminescence spectrum of a solar cell under applied bias to the external photovoltaic quantum efficiency of the device as measured at short circuit conditions [1]. So far, the theory has been verified for a wide range of devices and material systems and forms the basis of a growing number of luminesecence imaging techniques used in the characterization of photovoltaic materials, cells and modules [2–5]. However, there are also some examples where the theory fails, such as in the case of amorphous silicon. In our contribution, we critically assess the assumptions made in the derivation of the theory and compare its predictions with rigorous formal relations as well as numerical computations in the framework of a comprehensive quantum-kinetic theory of photovoltaics [6] as applied to ultra-thin absorber architectures [7]. One of the main applications of the photovoltaic reciprocity relation is the determination of quasi-Fermi level splittings (QFLS) in solar cells from the measurement of luminescence. In nanostructure-based photovoltaic architectures, the determination of QFLS is challenging, but instrumental to assess the performance potential of the concepts. Here, we use our quasi-Fermi level-free theory to investigate existence and size of QFLS in quantum well and quantum dot solar cells.

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10099-32, Session 8

Minibands modeling in strain-balanced InGaAs/GaAs/GaAsP cells

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In photovoltaics, the use of multi quantum wells (MQW) enables to tailor the optical absorption. This is particularly interesting in multijunction solar cells but it can also improve the efficiency of a single junction solar cell. This approach has proven to be efficient with the strain-balanced materials approach, which, to a well under compressive strain, associates a barrier under tensile strain. This allows the stacking of a large number of wells while preventing the formation of dislocations during crystal growth.

On the other hand, the use of barriers hinders the collection of the photo-generated carriers and more generally impedes the electronic transport in the MQW region. Indeed, since transport is a succession of thermal escape, assisted tunnel escape and, at best, direct tunneling across a barrier, the average carrier velocity is low (of about 10^4 cm s^-1). Finally this results in a large recombination rate and impacts both open-circuit voltage and short-circuit current.

However, in some conditions, minibands can occur in MQW regions. The wave function of carriers in minibands being Bloch waves, this means that propagation can be made efficient. Our theoretical study, based on quantum simulation (Green functions formalism) in InGaAs/GaAs/GaAsP cells, sheds light on minibands in which the average velocity of carriers is around 10^7 cm s^-1. However, we also show that, without an adapted design, such minibands are inefficient since they connect only a few wells. We will present some improvements related to the distance between barriers and the positioning of the MQW inside the cell to overcome these issues.

10099-33, Session 8

Optical contactless measurement of semiconductor thermoelectric transport properties

Francois Gibelli, Laurent Lombez, Jean-François Guillemoles, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France)

In view of the combinatorial approach to discovery of new thermoelectric materials, it is highly desirable to have fast measurement techniques, if possible with capabilities to access local fluctuations or gradients in material properties.

Using the generalized Planck& #39;s law of radiation [1] for fitting the photoluminescence spectra is the most appropriate technique to access the quasi Fermi level splitting and the temperature of the carriers in a semiconductor. These two parameters enable to determine Seebeck coefficients for the material as a new photo-Seebeck effect [2].

The absolutely calibrated photoluminescence intensity profile[3] with the spatial coordinates combined with Callen coupled transport equations and with the kinetic expression of the transport parameters under the relaxation time approximation enable us to determine: the Seebeck coefficient, the electrical conductivity, the thermal electron and hole conductivity, the mobilities, the diffusion coefficients and the heat transferred from the carriers to the lattice. All these parameters can be obtained either for electrons or for holes[4], even simultaneously, for intrinsic semiconductor in ambipolar regime.

The method has been applied to a multi-quantum well structure of InGaAsP. Since the luminescence comes from the wells, this method enables to access the transport properties in the plane of the wells inside the whole structure. Since photoluminescence does not require p-n junction nor high electrical conductivities for the measurement, this optical contactless measurement technique of thermoelectrinc transport parameters involving quasi-equilibrium carriers enables to access properties inside a given layer of the whole structure or in materials with very low conductivities.

We will also show the perspectives offered for the research of new thermoelectric materials.

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10099-34, Session 8

Characterisation of multi-junction solar cells by mapping of the carrier transport efficiency using luminescence emission

Amaury Delamarre, Paul Verdier, Kentaroh Watanabe, Masakazu Sugiyama, Yoshiaki Nakano, Jean-François Guillemoles, The Univ. of Tokyo (Japan)

Multijunction solar cells are currently the devices offering the largest conversion efficiencies of the solar radiation (above 45%). One strategy to further increase their efficiencies would be to operate them at higher sunlight concentrations, which is limited by the trade-off between shading and series resistances. We introduce here a new method for investigating this mechanism, by measuring maps of the current transport efficiency from luminescence images. This method brings finer information on the cell than electroluminescence methods, widely used so far for multi-junction cells, and offers much faster acquisition time than what could be obtained with a light beam induced current setup. The method has been theoretically and experimentally developed for single junction solar cells. The purpose of this communication is to assess its validity for multijunction solar cells, and to explain some results that can be counterintuitive at a first sight.

We experimentally investigate several multi-junction cell architectures. We demonstrate the applicability of the method on a complete range of applied electrical biases. The spatial resolution of the method allows us to discuss the different behaviour of the top and middle cells in terms of the front layer sheet resistance and lateral currents in the tunnel junction. Our approach is validated by comparing our results obtained from luminescence emission to standard electrical spectral response measurements and simulations.

10099-35, Session 8

Optoelectronic engineering of colloidal quantum-dot solar cells beyond the efficiency black hole: a modeling approach

Seyed Milad Mahpeykar, Xihua Wang, Univ. of Alberta (Canada)

Colloidal quantum dot (CQD) solar cells have been under the spotlight in recent years mainly due to their potential for low-cost solution-processed fabrication and efficient light harvesting through multiple exciton generation (MEG) and tunable absorption spectrum via the quantum size effect. Despite the impressive advances achieved in mobility of quantum dot solids and the cells' light trapping capabilities, the recent progress in CQD solar cell efficiencies has been very slow, leaving them behind other competing solar cell technologies. In this work, using comprehensive optoelectronic modeling and simulation, we demonstrate the presence of a strong efficiency loss mechanism, here called the "efficiency black hole", that can significantly hold back the improvements achieved by any efficiency enhancement strategy. We prove that this efficiency black hole is the result of sole focus on enhancement of either light absorption or charge extraction capabilities of CQD solar cells. This means that for a given thickness of CQD layer, improvements accomplished exclusively in optic or electronic aspect of CQD solar cells do not necessarily translate into tangible enhancement in their efficiency. The results suggest that in order for CQD solar cells to come out of the mentioned black hole, incorporation of an effective light trapping strategy and a high quality CQD film at the same time is an essential necessity. Using the developed optoelectronic model, the requirements for this incorporation approach and the expected efficiencies after its implementation are predicted as a roadmap for CQD solar cell research community.

10099-36, Session 9

Full 3D optoelectronic simulation tool for nanotextured solar cells *(Invited Paper)*

Jérôme Michallon, The Ile-de-France Photovoltaic Institute (France); Stéphane Collin, Lab. de Photonique et de Nanostructures (France)

Increasing efforts on the photovoltaics research have recently been devoted to material savings, leading to the emergence of new designs based on nanotextured and nanowire-based solar cells. The use of small absorber volumes, light-trapping nanostructures and unconventional carrier collection schemes (radial nanowire junctions, point contacts in planar structures,...) increases the impact of surfaces recombination and induces homogeneity in the photogenerated carrier concentrations. The investigation of their impacts on the device performances need to be addressed using full 3D coupled opto-electrical modeling.

In this context, we have developed a new tool for full 3D opto-electrical simulation using the most advanced optical and electrical simulation techniques. We will present an overview of its simulation capabilities and the key issues that have been solved to make it fully operational and reliable. We will provide various examples of opto-electronic simulation of (i) nanostructured solar cells with localized contacts and (ii) nanowire solar cells. We will also show how opto-electronic simulation can be used to simulate light- and electron-beam induced current (LBIC/EBIC) experiments, targeting quantitative analysis of the passivation properties of surfaces.

10099-37, Session 9

Broadband absorption enhancement in amorphous Si solar cells using metal gratings and surface texturing

Sara M. Al Menabawy, Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

The efficiencies of thin film amorphous Si (a-Si) solar cells are restricted by the small thickness required for efficient carrier collection resulting in poor light absorption. In this work, broadband absorption enhancement is theoretically achieved in a-Si solar cells by using nanostructured back electrode along with surface texturing. The back electrode is formed of Au nanogratings and the surface texturing consists of Si nanocones. The results were then compared to random texturing surfaces.

Three dimensional finite difference time domain (FDTD) simulations are used to design and optimize the structure. The Au nanogratings achieved absorption enhancement in the long wavelengths due to sunlight coupling to surface plasmon polaritons (SPP) modes. High absorption enhancement were achieved at short wavelengths due to the decreased reflection and enhanced scattering inside the Si absorbing layer. Optimizations have been performed to obtain the optimal grating's period integrated with the surface texturing. Comparisons have been made between random and periodic nanocones texturing. In addition, an enhancement factor (i.e. absorbed power in nanostructured device/absorbed power in reference cell) was calculated as a function of Si thickness.

10099-38, Session 9

Comprehensive study of various light-trapping techniques used for sandwiched thin-film solar-cell structures

Khaled A. Kirah, Ain Shams Univ. (Egypt); Sameh O. E. Abdellatif, The British Univ. in Egypt (Egypt); Rami Ghannam, Cairo Univ. (Egypt); Ahmed Khalil, Fayoum University (Egypt) and Arab Academy for Science, Technology & Maritime Transport (Egypt); Wagdy Anis, Ain Shams Univ. (Egypt)

Thin film solar cells (TFSCs) where first introduced as a low cost alternative to conventional thick ones. TFSCs show low conversion efficiencies due to the used poor quality materials having weak absorption capabilities and to thin absorption layers. In order to increase light absorption within the active layer, specially near its absorption edge, photon management techniques were proposed. These techniques could be implemented on the top of the active layer to enhance the absorption capabilities and/or to act as anti-reflecting coating structures. When used at the back side, their purpose is to prevent the unabsorbed photons from escaping through the back of the cell.

In this paper, we coupled the finite difference time-domain (FDTD) algorithm for simulating light interaction within the cell with the commercial

simulator Comsol Multiphysics 4.3b for describing carrier transports. In order to model the dispersive and absorption properties of various used materials, their complex refractive indices were estimated using the Lorentzian-Drude (LD) coefficients. We thus compared the absorption profile in the different layers of the cell, the improvements in photon absorption in the active layer and the power conversion efficiency achieved by 3 different sandwiching light trapping structures: textured surface, nanowires and dielectric nanospheres on the top of the active layer. Besides that, 1D, 2D and cascaded photonic crystal structures are added at the back side of the active layer. The simulation results are validated by previously measured experimental results when relevant.

10099-39, Session 9

Optimization of broadband omnidirectional antireflection coatings for solar cells

Xia Guo, Beijing Univ. of Technology (China)

Broadband and omnidirectional antireflection coating is a generally effective way to improve solar cell efficiency, because the destructive interference between the reflected and incident light could maximize the light transmission into the absorption layer. Several calculation methods have been developed to optimize the anti-reflective coating to maximize the average transmittance. However, because the solar irradiance of the clear sky spectral direct beam on a receiver plane at different positions and times are variable greatly, the optimization structures should be changed with the local position and solar spectrum. Here we report a new optimization method for anti-reflective coating with the incident quantum efficiency ?in as the evaluation function for practical applications. The two-layer and three-layer anti-reflective coatings are optimized over ? = [300, 1100] nm and ? = [0°, 90°] for cities of Quito, Beijing and Moscow. The ?in of such-optimized two-layer anti-reflective coating increases by 0.26%, 1.37% and 4.24% for the 3 cities, respectively, compared with that ocalculated by other methods. The results suggest that our optimization method combining the ant colony algorithm with specific solar irradiance spectra can effectively push solar cells towards higher quantum efficiency, thus enabling high utilization efficiency of solar irradiance.

10099-40, Session 9

Effects of intermediate plasmonic structures on the performance of ultra-thin-film tandem solar cells

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Although solar cells can meet the increasing demand for energy of modern world, their usage is not as widespread as expected because of their high production cost and low efficiency. Thin-film and ultra-thin-film solar cells with single and multiple active layers are being investigated to reduce cost. Additionally, multiple active layers of different energy bandgaps are used in tandem in order to absorb the solar spectra more efficiently. However, the efficiency of ultra-thin-film tandem solar cells may suffer significantly mainly because of low photon absorption and current mismatch between active layers. In this work, we study the effects of intermediate plasmonic structures on the performance of ultra-thin-film tandem solar cells. We consider three structures— each with a top amorphous silicon layer and a bottom micro-crystalline silicon layer, and an intermediate plasmonic layer between them. The intermediate layer is either a metal layer with periodic holes or periodic metal strips or periodic metal nanoclusters. Using a finite difference time domain technique for incident AM 1.5 solar spectra, we show that these intermediate layers help to excite different plasmonic and photonic modes for different light polarizations, and thereby, increase the absorption of light significantly. We find that the short-circuit current density increases by ~12%, ~6%, and ~9% when the intermediate plasmonic structure is a metal hole-array, strips, and nano-clusters, respectively, from that of a structure that does not have the intermediate plasmonic layer.

10099-41, Session PWed

Sub-micrometer particle size distribution analysis utilizing multi-angle dynamic light scattering

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Multiangle Dynamic light scattering (MDLS) provides a better estimate of particle size distribution(PSD) than single-angle DLS. The utility of combining the light intensity autocorrelation functions from a number of measurement angles, which are influenced by different scattering characteristics and dynamics at different scattering angles, has been demonstrated. In this work, a measuring system was developed to detect the MDLS of unimodal and multimodal PSD. This system yields satisfying reconstruction of the particle size distribution but demands suitable angle set for measuring, which has not been discussed before. So we tested 600nm unimodal PSD and 500nm and 800nm bimodal PSD at one angle and multiple angles respectively. The inversion results show the six-angle analysis should be the optimal number. To further study the most fitting angle range for six-angle analysis, three different angle sets were tested using the above unimodal and bimodal PSDs. We found that dynamic light scattering intensity of particle groups measured at six scattering angles chosen from range got more accurate reconstructed PSDs than other angle sets for both unimodal and multimodal PSDs because a sufficient wide angle span is covered, and sufficient variation of the scattering intensity with the angles as well as the appropriate angle number is achieved. However, existing algorithms do not suit both unimodal and multimodal distributions and could be applied directly to the inversion problem for MDLS unless they could be combined with the method for estimating the weighting coefficients. To obtain the more accurate inversion results, especially for multimodal PSD, we propose a recursive regularization method-Recursion Nonnegative Tikhonov-Phillips-Twomey (RNNT-PT) algorithm for estimating the weighting coefficients and PSD from MDLS data. This is a self-adaptive algorithm which distinguishes characteristics of PSDs and chooses the optimal inversion method from Nonnegative Tikhonov (NNT) and Nonnegative Phillips-Twomey (NNPT) regularization algorithm efficiently and automatically.

10099-42, Session PWed

Selective optical contacting for solar spectrum management

Jianfeng Yang, Weijian Chen, Bo Wang, Zhilong Zhang, Shujuan Huang, Santosh Shrestha, Xiaoming Wen, Robert Patterson, Gavin Conibeer, The Univ. of New South Wales (Australia)

Solar spectrum management using up/down conversion is an important method to reduce both the sub-band-gap and over-band-gap energy loss during photovoltaic conversion. Apart from the internal carrier conversion efficiency of the material, an efficient optical coupling between the conversion material and solar cell device is also crucial to boost the output power efficiency. Here, we demonstrate a near-field resonant transfer process by nano-optical-cavity structures. By increasing both the optical emission and reabsorption through cavity mode in a near-field region, an efficient optical contacting is realized between the luminescence emitter and the band edge of photovoltaic active material. Selective field coupling enhancement is not only required to avoid further thermalization loss in the photovoltaic device but also being helpful to promote the yield of up/down conversion, especially for the conversion materials with continuous

electronic energy states such as hot carrier and multiple exciton generation (MEG). In this paper, the photonic crystal cavity is used to build the optical contacting structure which integrates a planar thin silicon film (acting as a photovoltaic device) and conversion material (simulated by InN thin film). The lossy resonant mode is numerically simulated by FDTD method while the overall optical transfer is calculated by a rigorous Green's function approach. A detailed-balance model is used to estimate the overall conversion efficiency by considering the thermodynamical impact of optical enhancement on both the solar cell and conversion material. The result shows a considerable increase in the overall conversion efficiency. More details will be reported in SPIE Photonics West 2017.

10099-43, Session PWed

Multifunctional TiN nanowires for wide band absorption in organic solar cells

Sara M. Al Menabawy, The American Univ. in Cairo (Egypt); Qiaoqiang Gan, Univ. at Buffalo (United States) and The State Univ. of New York (United States); Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

One of the key issues limiting the efficiency of organic solar cells is the narrow absorption band of the polymer active layer. Thus, a huge amount of the incident sunlight is lost. Here, a new structure is theoretically proposed achieving wide band absorption in organic solar cells using multifunctional TiN nanowires.

In addition to the plasmonic properties of TiN, it was reported that TiN has the capability to produce free carriers upon light absorption. Thus, the structure is based on the ability to collect these photo-generated carriers. The structure consists of TiN back electrode, 30 nm P3HT:PC70BM, 10 nm PEDOT:PSS and 20 nm ITO. Short TiN nanowires are added inside the active layer and connected to the TiN back electrode. The TiN length was fixed to 25 nm and the diameter and period were varied for optimizing the structure. Using the combination of TiN and polymer significantly broadened the absorption band due to the ability of TiN to localize light inside P3HT:PC70BM in addition to its ability to absorb light at longer wavelengths. The optimized structure enhanced the absorbed power by 95% and the optimal short circuit current by 123% over the same structure without the TiN nanowires. Electric field distribution is studied at different wavelengths to gain further insight on the localization of light inside the structure.

10099-44, Session PWed

Spectral properties of Al1-xGax AsSb in avalanche photodiodes for security applications

Shumithira Gandan, Juan S Dominguez Morales, Tyndall National Institute (Ireland) and Cork Institute of Technology (Ireland); Xinxin Zhou, Chee Hing Tan, Jo Shien Ng, The Univ. of Sheffield (United Kingdom); Tomasz J. Ochalski, Tyndall National Institute (Ireland) and Cork Institute of Technolog (Ireland)

Operation in the mid wave-infrared (MWIR) region is necessary for security applications such as border surveillance and 3D imaging. Avalanche photodiodes (APDs) provide amplification of low power signals in these applications due to its avalanche gain. Linear-mode Separate Absorption Multiplication (SAM) APDs that operate at the MWIR region are thus the topic of interest in this work.

Ternary alloys of AlAsSb lattice-matched to InP substrates are expected to eradicate the band-to-band tunnelling current that has limited the development of InP based APDs. In addition, recent investigation has encouraged the introduction of Gallium into AlAsSb to reduce the surface leakage current.

Optical spectroscopy techniques such as photoluminescence (PL) and photoreflectance (PR) have been employed to determine the effect of Gallium content on two different samples with varying Gallium composition (15% and 5%). This allows examination of the physical aspects and stability of the structural layers in the AlGaAsSb alloy. PL experiments conducted at 10K to 100K produced three distinct features at 1.42eV, 1.38eV and 1.34eV.

The peak at 1.42eV red shifted whereas the other two peaks increased in FWHM with corresponding temperature rise. Franz-Keldysh oscillations at the intermediate-field limit were predicted based on the PR measurements done for use at room temperature and 77K which necessitates fittings with Airy functions. It can be established that higher Gallium composition results in an increase of overall PL intensity while reducing the broadening parameters in AlGaAsSb PR spectra.

10099-45, Session PWed

Application of concentrating plasmonic luminescent down-shifting layers for photovoltaic devices

Hind Ahmed, Subhash Chandra, Mehran Rafiee, Arnima Sethi, Sarah J. McCormack, Trinity College Dublin (Ireland)

Photovoltaic (PV) research has focused on achieving higher PV conversion efficiency at lower cost. Plasmonic Luminescent Down-Shifting (pLDS) is a new optical approach to improve a PV device efficiency by using plasmonic coupling between luminescent materials and metal nanoparticles (MNP). The luminescent material in the composite layer is used to convert the high energy photons to lower energy photons before they reach the solar cell. Generally luminescent down-shifting layers suffer from self-absorption which undermines their efficiency. The downshifted photons are re-absorbed by the material within the down shifting layer which is a function of the optical path length, concentration, and Stokes shift. MNP however exhibiting surface plasmon resonance (SPR) have shown to enhance the optical properties of the luminescent material. Concentrating structure of pLDS composite layers (c-pLDS) containing lumogen yellow dye and silver nanoparticles (Ag NPs) were fabricated. The c-pLDS structures allowed for a wider absorption range of wavelengths with a strong energy transfer that red shifts photons to wavelengths which gives greater spectral response of solar cells. Fabricated c-pLDS devices are presented along with their optical and electrical characterization. The experimental results obtained were compared with a Finite Difference Time Domain (FDTD) model. The results presented have shown significant enhancement in absorption, fluorescence emission and electrical output of the c-pLDS photovoltaic devices studied.

10099-46, Session PWed

Low-cost tandem solar cells

Hal Gokturk, Ecoken (United States)

Tandem solar cells consisting of several layers which absorb different parts of the solar spectrum are known to have the highest efficiency but cost of producing them remains an obstacle to widespread adoption.

What is proposed in this paper is to make two inorganic films on two separate substrates and to join them with an intermediate organic layer to form a three layer tandem cell. Both inorganic films must be easy to produce to lower the cost and defect tolerant to achieve high efficiency.

The inorganic film facing the sunlight is a wide bandgap semiconductor such as zinc oxide (ZnO) formed on TCO coated glass. The inorganic film serving as the bottom layer of the tandem structure is a narrow bandgap perovskite such as methyl ammonium lead iodide ($CH_3NH_3PbI_3$) formed on a second substrate.

The intermediate organic layer is a charge transfer complex consisting of an electron donor and an electron acceptor, for example TTF/TCNQ. Desirable properties are a) an absorption spectrum intermediate between the ZnO film and the perovskite film; b)good adhesion of the electron acceptor to the top ZnO film and the electron donor to the bottom perovskite film.

Since charge transport properties of organic materials are not as good as inorganic ones, the organic layer is expected to be only several nm thick, filling the gap between the top and bottom layers when they are pressed against each other.

Currently, adhesion of various charge transfer complexes to the inorganic films are being examined and results will be reported during the presentation.

10099-47, Session PWed

MIMIM photodetectors using plasmonically-enhanced MIM absorbers

Sina Abedini Dereshgi, Ali K. Okyay, Bilkent Univ. (Turkey)

We demonstrate super absorbing metal-insulator-metal (MIM) stacks and MIMIM photosensitive devices operating at visible and near-infrared (VIS-NIR) spectrum, where absorbing (top) MIM and photocollecting (bottom) MIM can be optimized separately. We investigate different bottom metals in absorbing MIM with nanoparticles realized by dewetting of silver thin film on top. While gold and silver have conventionally been considered the most appropriate plasmonic absorbers, we demonstrate different absorbing metals like aluminum and specifically chromium, with its plasma frequency happening at 850 nm, as more efficient layers for absorption. Absorption in chromium hits 82 percent around 1000 nm. We provide convincing evidences by doing reflection experiment and computational simulations for absorbing MIM part. We also suggest for the first time investigating quality factor for surface plasmon polariton of metal or coherently, loss tangent of absorbing metals which are reliable tools for engineering different metal layers. They reveal that despite the fact that gold and silver are good plasmonic scatterers in VIS-NIR and reliable absorbers in VIS region, they are not proper choices as absorbers for NIR applications. Once the most optimum absorbing designs are pointed out, we integrate them on top of another metal-insulator to form MIMIM photodetectors with tunneling photocurrent path. The final optimized sample consisting of silver – hafnium oxide – chromium – aluminum oxide – silver nanoparticles (from bottom to top) has a dark current of 7nA and a photoresponsivity peak of 0.962 mA/W at 1000 nm and a full width at half maximum of 300 nm, while applied bias is 50 mV and device areas are 300 ?m x 600 ?m. This photoresponse shows 70 times enhancement compared to former reported spin coated rare nanoparticle MIMIMs.

10099-48, Session PWed

Electro-optical analysis of Si-tapered nanowires/low-band-gap polymer hybrid solar cells

Sara M. Al Menabawy, Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

Three dimensional optical and electrical simulations are performed to assess the design requirements for obtaining highly efficient tapered Si nanowires (TSiNWs)/polymer hybrid solar cells. To avoid the complex fabrication processes of Si p-n junctions, the TSiNWs are coated with a conductive polymer forming a large junction area between both materials and making the charge separation more efficient. The addition of PEDOT:PSS has been reported previously where the absorption occur in the Si only. P3HT:PCBM has been also used on top of Si nanostructures to enhance the absorption. However, the maximum absorption of P3HT and Si are in the same range resulting in competence between the absorption of each material. Thus, thick Si substrates are still needed to achieve decent absorption in these devices.

We report a broadband absorption spanning the whole visible and near infra-red range of the solar spectrum with only 5 Microns TSiNWs coated with a low band gap polymer. The tapered structure provides efficient light trapping for the incident light enhancing the absorption in the short wavelengths. The addition of the low band gap polymer (pBBTDPP2:PCBM) significantly enhanced the absorption at long wavelengths (700-900nm). Thus, broadband absorption is attained without the need of thick Si substrates. Full 3D optical simulations were performed to optimize the polymer thickness and compare between the enhancements in absorption for different polymers. In addition, the absorption of conventional SiNWs and TSiNWs are analysed with full optical, modal and electrical comparison between both structures with and without the addition of the polymer.

10099-49, Session PWed

Dark current modeling in the mid-wavelength infrared pin photodiode based on the InAs/GaSb superlattice

Ha Sul Kim, Hun Lee, Chonnam National Univ. (Korea, Republic of); Jun Oh Kim, Sang Jun Lee, Korea Research Institute of Standards and Science (Korea, Republic of); Brianna Klein, Sanjay Krishna, The Univ. of New Mexico (United States)

The theoretical and experimental results are presented for current - bias and dynamic resistance-bias characteristics of 10 Monolayer (ML) InAs/10 ML GaSb type II superlattice mid infrared pin diodes. By measuring the dc characteristics in the temperature range 30-250K, the dark current mechanism was studied. The diffusion current dominates at the high temperature (>150K) and in the low reverse bias. On the other hand, at the lower temperature (<100K), surface leakage current is the key leakage current source. We will also show the electrical dark current behaviors depending on the passivation materials such as Si3N4, SiO2, and Al2O3.

10099-50, Session PWed

Temperature dependence of quantum-wire intermediate-band solar cells

Mirsaeid Sarollahi, Vasyl P. Kunets, Yuriy I. Mazur, Univ. of Arkansas (United States); Mansour Mortazavi, Univ. of Arkansas at Pine Bluff (United States); Gregory J. Salamo, Morgan Ware, Univ. of Arkansas (United States)

This work investigates the performance of an intermediate band solar cell (IBSC) structure based on InGaAs/GaAs lateral quantum wires. Un-optimized structures using the same IB material approach based on quantum wires have demonstrated an increase in solar conversion efficiency in comparison with reference GaAs P-I-N diode devices. In order to further understand the physics behind this increase, an optimized structure was developed and characterized demonstrating more than a 50% improvement in conversion efficiency. The External Quantum Efficiencies (EQE) of doped and undoped samples have been measured using these optimized designs. We will present results of varying both applied bias and temperature on the EQE of these IBSC devices to highlight the advantages of such a structure.

10099-51, Session PWed

Impact of natural photosensitizer extraction solvent upon light absorbance in dye-sensitized solar cells

Suriati Suhaimi, Univ. Malaysia Perlis (Malaysia); Siti Zubaidah Mohamed Siddick, Universiti Malaya (Malaysia); Nor Azura Malini B. Ahmad Hambali, Mohamad Halim Abdul Wahid, Vithyacharan Retnasamy, Univ. Malaysia Perlis (Malaysia); Mukhzeer Mohamad Shahimin, National Defence Univ. of Malaysia (Malaysia)

Natural pigmentations of Ardisia, Bawang Sabrang, Harum Manis mango, Oxalis Triangularis and Rosella were used to study the general trend in performance of dyes as photosensitizer in application of dye-sensitized solar cells (DSSCs) based on optical light absorbance and photoelectrochemical characteristic. From the Ultraviolate Visible Spectrophotometer with the recorded absorption measurements in the range between 400 nm to 800 nm, the dyes extracting of Rosella and Oxalis Triangularis in water solvent exhibited the conversion efficiency up to 0.68% and 0.67%, respectively. The light absorbance peak for dye extracting of Ardisia, Bawang Sabrang, Oxalis Triangularis and Rosella in water and ethanol solvent resulted in range between 500 nm to 650 nm, while the Harum Manis mango resulted the broader spectra in both water and ethanol solvent. The light absorbance spectra each of the dyes shows the changes of the spectra trends with the shifted wavelength when the dye extracting adsorbed onto TiO_2 film surface that might influence the absorption of light by TiO_2 particle in the visible region. The capabilities of the dyes to absorb light onto the TiO_2 film with the shifted of wavelengh when the dye bonded onto the TiO_2 photoanode was found to be significant with the current-voltage conversion of the cell.

10099-52, Session PWed

Temperature effect of natural organic extraction upon light absorbance in dye-sensitized solar cells

Suriati Suhaimi, Univ. Malaysia Perlis (Malaysia); Siti Zubaidah Mohamed Siddick, University of Malaya (Malaysia); Vithyacharan Retnasamy, Mohamad Halim Abdul Wahid, Nor Azura Malini B. Ahmad Hambali, Univ. Malaysia Perlis (Malaysia); Mukhzeer Mohamad Shahimin, National Defence Univ. of Malaysia (Malaysia)

Natural organic dyes that contain pigment which safely extracted from plants are used as a sensitizer with promising a low cost fabrication plus environmental friendly in DSSCs. Ardisia, Bawang Sabrang, Harum Manis mango, Oxalis Triangularis and Rosella showed the different absorption peaks when the extracting dyes was heated at different temperature. Hence, these were used to determine the conversion efficiency based on the impacts of dyes extracting temperature. Dyes extracting in water resulted the best performance at temperature at 100 except for Harum Manis mango, while in ethanol, the optimum temperature was obtained between the room temperature and 50. The absorption spectrum in water showed the broader absorption with wide range of absorption wavelength compared in ethanol solvent that resulted the absorption peak for Ardisia, Harum Manis mango and Rosella between 450 nm to 550 nm. The highest conversion efficiency achieved by Oxalis Triangularis extracting in water solution at temperature 100 about 0.96% which is corresponds to the broader absorbance trends. in this study. Thus, the optimum condition extracting temperature for dye extracting in water and ethanol is in between room temperature and boiling points of water. Hence, Ardisia, Bawang Sabrang, Harum Manis mango, Oxalis Triangularis and Rosella can be as alternative for photosensitizer and the impacts of temperature upon the light absorbance can be evaluated more for further study.

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10100-1, Session 1

Recent advances on pumping schemes for mid-IR PCF lasers *(Invited Paper)*

Mario C. Falconi, Giuseppe Palma, Politecnico di Bari (Italy); Florent Starecki, Virginie Nazabal, Johann Troles, Jean L Adam, Université de RENNES1 (France); Stefano Taccheoc, University of Swansea (United Kingdom); Maurizio Ferrari, CNR (Italy); Francesco Prudenzano, Politecnico di Bari (Italy)

The design of two pumping schemes for mid-IR lasers based on photonic crystal fibers (PCFs) is illustrated. The PCFs considered in both pumping schemes are made of dysprosium-doped chalcogenide glass Dy3+:Ga5Ge20Sb10S65. The two optical sources are accurately simulated by taking into account the spectroscopic parameters measured on a rare earth-doped glass sample. A home-made numerical model based on power propagation equations and solving the ion population rate equations of the rare earth is employed and a realistic feasibility investigation is performed. The first pumping scheme is based on optical power pumping at 1700 nm wavelength and allows beam emission close to 4400 nm wavelength, the efficiency is increased till about ? = 22% by integrating a suitable optical amplifier after the laser cavity. The second pumping scheme exploits two pump beams at the wavelengths close to 2800 nm and 4100 nm and enables a laser emission close to 4400 nm wavelength with an efficiency higher than ? = 30%. Both these sources could promote a number of promising applications in different areas such as satellite remote sensing, laser surgery, chemical/biological spectroscopy and mid-IR optical communication.

10100-2, Session 1

Ho-nanoparticle-doping for improved high-energy laser fibers

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Holmium-doped fiber lasers (HoDFLs) operate near 2 microns, which is in a wavelength region that is both eye-safer and in a window of high atmospheric transmission, making them attractive for high energy applications. A significant issue is multiphonon quenching due to the high phonon energy ~1100 cm-1 of the silica host, which complicates power scaling due to reduced lifetimes and increased heating. For example, the measured lifetime of Ho3+ in silica fibers is <1 ms, compared with 17 ms predicted by Judd-Ofelt calculations. Nanoparticle (NP) doping is a new technique that is being developed for rare-earth doped silica fibers where the structure surrounding the ions is developed chemically prior to doping into the silica core. Previously, we have shown that Er ions are incorporated into a cage of aluminum and oxygen ions in Er:Al2O3 NPs, thereby substantially reducing Er-Er ion interactions to improve high power performance. Likewise, we have incorporated Ho3+ ions into various NPs, such as LaF3, Al2O3 and Lu2O3, to shield them from the silica glass matrix. A concern with this technique is OH incorporation from the aqueous NP processing since there is a combination absorption band of the OH fundamental mode and the SiO4 tetrahedron vibration near 2.22 microns. With careful drying of the soot preform we measure [OH] ~1 ppm, which is acceptable for high energy lasers. We report improved lifetimes and a comparison of the laser properties between solution-doped and NP-doped fibers. Results indicate improved potential for power scaling.

10100-3, Session 1

Diode-pumped laser based on crystalline-core/crystalline-clad fibers

Jun Zhang, Youming Chen, Tigran Sanamyan, U.S. Army Research Lab. (United States); Shizhuo Yin, Clair Luo, General Opto Solutions, LLC (United States); Mark Dubinskii, U.S. Army Research Lab. (United States)

We report laser experimental results obtained with the Yb3+-doped core, fully crystalline, double-clad (DC) fibers. The investigated DC fibers with the 'crystalline core/crystalline clad' (CCCC = C4) architecture were fabricated using a liquid phase epitaxial growth (LPE) of undoped single-crystalline YAG cladding around the 100 μm single-crystalline Yb:YAG core separately grown by a laser heated pedestal growth (LHPG) technique. In our laser experiments the 30-70 mm long fully crystalline DC fibers were placed in an external plano-plano cavity with butt-coupled mirrors, and tested in the core-guided regime. The C4-structured fibers were free-space cladding-pumped by either the 969-nm or 976-nm laser diode modules within the numerical aperture (NA) of 0.55, which has not even fully utilized the cladding NA. The emitted core-guided low-NA (0.076) fiber laser output was fully characterized, spectrally and spatially, and optical-to-optical laser efficiency of well over 10% has been demonstrated. This corresponds to over ~50-fold brightness enhancement despite the relatively low optical-to-optical laser efficiency in these first experiments.

10100-4, Session 1

Single-crystal fiber lasers for high-power applications

Shyam S. Bayya, Woohong R. Kim, Charles Askins, Jason D. Myers, Steve R. Bowman, Daniel J. Gibson, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States); John R. Peele, Rajesh Thapa, Sotera Defense Solutions, Inc. (United States); Daniel L. Rhonehouse, Univ. Research Foundation (United States)

Single crystal fibers are currently being developed for high power single frequency lasers in 1-2 μm region. Crystal fibers offer several advantages over traditional glass fibers such as silica fiber due to their higher thermal conductivity and higher stimulated Brillouin scattering (SBS) thresholds, along with excellent environmental stability and higher doping concentrations. Yb3+ and Ho3+ doped single crystal YAG fibers with diameters down to 17 μm and lengths >1m long have been grown using our state-of-the-art Laser Heated Pedestal Growth system. Single and double cladded rare earth doped crystal fibers have been fabricated using glasses where optical and physical properties were precisely matched to the core single crystal fiber. We also show successful fabrication of all crystalline core/clad fibers where thermal and optical properties are superior over glass based fibers. Various fabrication methods, optical characterization and gain measurements on these clad fibers will be reported.

10100-5, Session 1

High-pulse-energy single-frequency fiber lasers

Shibin Jiang, AdValue Photonics, Inc. (United States)

No Abstract Available

10100-6, Session 2

A performance study of Nd-based stoichiometric random lasers *(Invited Paper)*

Joaquín Fernández, Jon Azkargorta, Iñaki Iparraguirre, Rolindes Balda, Univ. del País Vasco (Spain)

Rare earth stoichiometric powder hosts have received the most attention for random laser (RL) action1,2. In contrast to other laser hosts where the active ion is dispersed as a dopant in a crystalline matrix, stoichiometric hosts are pure chemical compounds of rare earth (RE) ions. In principle, the main variable that controls the quenching of the desired luminescence is the non-radiative energy transfer process between RE ions. In a microsecond time scale the high concentration of Nd^{3+} ions might give rise to short-range spatial energy transfer in the metastable level, as well as to long-range spatial energy migration among Nd^{3+} ions and thus, huge losses might be expected which would affect the threshold and slope efficiency for laser action. However, the fast build up of the random laser pulse makes the nonradiative losses produced by quenching concentration much less important than in a conventional laser.

This work presents a comparative study of the random lasing performance of several Nd based stoichiometric compounds, including threshold and absolute slope efficiencies together with a discussion about the fundamental parameters which control the random laser operation in this kind of compounds.

10100-7, Session 2

High-efficiency Q-switched Yb:YLF laser at 995 nm with second harmonic conversion

Nikolay E. Ter-Gabrielyan, Viktor Fromzel, Mark Dubinskii, U.S. Army Research Lab. (United States)

We report on a highly efficient, diode-pumped, Q-switched, cryogenically cooled Yb:YLF laser operating at 995 nm. A free space coupled, linearly polarized 960 nm laser diode module was used for pumping the crystal in its sigma absorption band. Laser performance has been studied in a pulse repetition frequency (PRF) range from 500 Hz to 10 kHz using both acousto-optic (AO) Q-switching for all PRFs and electro-optical switching at 500 Hz. A nearly diffraction-limited beam quality was observed across the entire PRF range.

In a pure CW mode, without the intracavity Q-switching cell, the laser demonstrated an 82% slope efficiency. In the 10 kHz AO Q-switching mode with 60 nsec pulsewidth, it yielded 50 W of the average power with a slope efficiency of 74%. The 10 kHz regime is of major importance for applications benefiting most from very high PRFs.

With the PRF slowing from 10 kHz to 500 Hz, an average power had to be intentionally reduced from 50 W to 16 W in order to avoid damaging the intracavity optics. Nevertheless, the output pulse energy increased from a 2.5 mJ/pulse at 10 kHz PRF to a 32 mJ/pulse at 500 Hz – which was in good agreement with our laser model.

The laser was optimized for second harmonic generation (SHG) at the PRF of 500 Hz with the pulse duration of 20 ns. SHG was obtained in an LBO crystal positioned outside the laser cavity. The maximum conversion efficiency of 50% has been achieved.

10100-8, Session 2

Ball-milled nano-colloids of rare-earth compounds as liquid gain media for capillary optical amplifiers and lasers

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Nano-colloids and nano-crystals doped with ions of rare-earth elements have recently attracted a lot of attention in the scientific community due to their potential applications as biomarkers, fluorescent inks, gain media for lasers and optical amplifiers. Many rare-earth doped materials of different compositions, shapes and size distribution have been prepared by different synthetic methods, such as chemical vapor deposition, sol-gel process, micro-emulsion techniques, gas phase condensation methods, hydrothermal methods and laser ablation. In this paper micro-crystalline powder of the rare-earth-doped compound $NaYF_4$:Yb^{3+},Er^{3+} was synthesized using a simple wet process followed by baking in open air. Under 980 nm diode laser excitation strong fluorescence in the 100 nm band around 1531-nm peak was observed from the synthesized micro-powder. The micro-powder was pulverized using a ball mill and prepared in the form of nano-colloids in different liquids. The particle size of the obtained nano-colloids was measured using an atomic force microscope and a dynamic light scatterometer. The size of the nano-particles was close to 100-nm. The nano-colloids were utilized as a filling media in capillary optical amplifiers and lasers. The gain of a 7-cm-long capillary optical amplifier (150-micron inner diameter) was as high as 6 dB at 200 mW pump power. The synthesized nano-colloids and the active optical components using them can be potentially used in optical communication, signal processing, optical computing, and other applications.

10100-9, Session 2

Spectroscopic characterization of excited-state absorption in Co:ZnSe/ZnS crystals

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Co^{2+}:II-VI chalcogenide (e.g. ZnSe, ZnS) crystals exhibit broad emission in the 3-4μm spectral range with absorption peaks at ~0.75μm, ~1.5μm, and ~2.9μm which can be used for excitation. Laser oscillation of Fe^{2+} with wavelength ~4μm has been demonstrated at 14K in Co:Fe:ZnSe/ZnS under energy transfer from Co^{2+} ions. However, recent efforts in obtaining laser oscillation in Co^{2+}:ZnSe/ZnS crystals have been unsuccessful. This can potentially be explained by excited state absorption at the 4T2(F)?4T1(F) transition. In addition, the laser oscillation in Co:Fe:ZnSe/ZnS co-doped crystals was only observed at temperatures under 21K. We report measurements of Co:ZnSe/ZnS absorption and emission at room temperature and 14K as well as estimates of excited state absorption from these measurements. Also, the results of experiments showed increase of absorption at 2.94μm under alexandrite laser excitation in Co:ZnS, which could result from excited state absorption. The lifetime of induced absorption was ~100μs, which is close to the ~200μs lifetime of the 4T2 level. The model of excited state absorption at low temperature predicts strong absorption over the emission spectrum of Co^{2+} in ZnSe, which can explain the negative lasing results. The loss of laser oscillation in co-doped crystals with increased temperature can be explained by the broadening of excited state absorption of Co^{2+}. The spectroscopic measurements of the excited state absorption spectrum of Co:ZnSe/ZnS will be presented at the conference.

10100-10, Session 2

Charging process and mechanisms of the persistent luminescence in Cr3+-doped oxide-based spinel nanoparticles

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Persistent luminescence in the red/near-infrared range has great potential for bioimaging because there is no need for in situ excitation, there is negligible autofluorescence background and deep tissue penetration in optical detection. However, it is challenging to synthesize monodispersed nanosize NPs along with high quantum yield and long persistent luminescence. The nanoparticles (ZnGa2O4:Cr3+(0.5%)) are synthesized by soft chemistry using microwave heating in aqueous media. These very small size nanophosphors (around 9nm) present interesting long persistent luminescence after annealing at 1000°C and they can be excited both under UV and under LED excitation within the visible range. The nanoparticles keep their small size as they are coated with a silica layer which can then be removed by a chemical etching with NH5F2.

We better understand the origin of the persistent luminescent properties of the nanomaterial using electron paramagnetic resonance in order to study the chromium environment, 71Ga nuclear magnetic resonance to get information on the gallium ions repartition (tetrahedral or octahedral site) in the structure and by thermoluminescence to investigate trapping and detrapping processes.

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10100-11, Session 3

Blue light emission from trivalent cerium doped in sol-gel silica glass

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Rare earths in glass matrices are promising for active optical devices as amplifiers and lasers. Emission originating from d-f transitions in sol-gel glass has not been studied very often, while that based on f-f transitions were widely utilized. However, d-f emission in rare earths is very important because of their strong oscillator strength and broad emission widths suitable for the application to scintillators and solid-state lasers. Co-doping of aluminum in sol-gel synthesis was known to be effective for the emission enhancement of trivalent terbium and europium. Recently, we employed the co-doping to cerium and europium in sol-gel glass to succeed in the observation of strong blue light emission originating from d-f transitions. Glass samples were prepared with conventional sol-gel process where tetramethylorthosilicate was hydrolyzed in the mixture of water, ethanol and dimethylformamide with nitric acid catalyst. After adding cerium nitrate and aluminum nitrate, the solution experienced drying for half a month followed by calcination at 1,050 degree under air environment. When molar ratio of cerium to silicon was adjusted at 0.1% and Al concentration was varied in 0.1 ~ 2.0%, transparent glass products showed bright blue photoluminescence under UV light. The fluorescence lifetimes were found to be about 80 ns, indicating that the emission was due to d-f transitions. For europium, the same process was employed but hydrochloric acid catalyst, giving bright blue luminescence. Considering the simplicity of the process, blue phosphors based on sol-gel glass will be very promising for future applications.

10100-12, Session 3

Rare-earth-doped optical-fiber core deposition using full vapor-phase SPCVD process

Alexandre Barnini, Thierry Robin, Benoît Cadier, Thierry Gotter, iXBlue SAS (France); Gérard P. Aka, Ecole Nationale Supérieure de Chimie de Paris (France); Daniel Caurant, Cédric Guyon, Institut de Recherche de Chimie Paris (France)

One key parameter in the race toward ever-higher power fiber lasers remains the rare earth-doped optical core quality. Modern Large-Mode-Area (LMA) fibers require a fine radial control of the core refractive index (RI) close to the silica level. These low RI are achieved with multi-component materials that cannot be readily obtained using conventional solution doping-based CVD technology. This paper presents a systematic study of such optical material obtained through a full-vapor phase Surface Plasma Chemical Vapor Deposition (SPCVD). The SPCVD process generates straight glassy films on the inner surface of a thermally regulated synthetic silica tube under vacuum. We have investigated ytterbium doped aluminosilicate material and adjusted the refractive index using alternatively fluorine, boron and phosphorous. Each single element contributes stably to the RI; however once mixed, detrimental effects, such as diffusion, alter the flatness of the RI profile which needs to be taken into account through recipe. Our materials yielded, when used in optical fibers with numerical apertures ranging from 0.06 to 0.09, power conversion efficiency between 65 and 75% and low background losses below 20 dB/km at 1100nm. Photodarkening has been measured to be similar to equivalent MCVD-based fibers. The use of cerium as a co-dopant allowed for a complete mitigation of this laser lifetime detrimental effect. The SPCVD process enables high capacity preforms and is particularly versatile when it comes to radial tailoring of both rare earth doping level and RI. Large core diameter preforms - up to 4mm - were successfully demonstrated.

10100-13, Session 3

Yb-doped Polarizing Fiber

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An ytterbium doped, single polarization, polarizing fiber is demonstrated. The fiber offers the opportunity to build single polarization, all-fiber, fiber lasers without the need for free-space polarizing components.

Traditional single polarization fiber lasers utilize PM gain fiber with a single polarization stimulation signal. Whilst this results in an approximation to a single polarization laser, the spontaneous emission from the unstimulated polarization state limits PER. The PER is further limited as the stimulated signal is prone to crosstalk. Beyond PER, amplitude modulation of the stimulated signal is critical for controlling the peak power of an optical pulse, particularly for high energy lasers. If any light leaks into the unstimulated axis it travels at a different velocity to the stimulated axis and can cross-couple back into the stimulated axis, creating an interference effect which leads to amplitude modulation on the signal pulse. Single polarization Yb-doped fiber ensures that light on the fast axis is constantly

attenuated, ensuring that light on the unstimulated axis cannot propagate and thus cannot degrade PER or create amplitude modulation.

In this paper we report how the single polarization Yb-doped fiber has been achieved by combining Bow-Tie PM fiber modified chemical vapor deposition (MCVD) with rare-earth solution doping technology. The fiber has a single-polarization window of 50nm centred at the 1060 nm and a PER of >30dB. The PER as a function of power has been characterized and shows good stability over a wide range. In a lasing configuration an optical conversion efficiency of ~75% was achieved.

10100-14, Session 3

Red persistent luminescence and traps control by cationic substitutions in NaNbO3: Pr3+

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Currently, the development of efficient red-emitting persistent phosphor is still an ongoing challenge. Pr3+ is a good candidate for its transition 1D2-3H4 at about 610 nm. Emission from 3P0 vanished in NaNbO3: Pr3+ at room temperature. This is related to the presence of a low-lying intervalence charge transfer (IVCT) state, which quenches the emission from 3P0 level. For good persistent luminescence traps should be located at around 0.7 eV from IVCT or conduction bands and cationic substitutions Na by K, Li and Cs as well as Nb by Ta in NaNbO3: Pr3+is proposed to enhance the persistent luminescence.

10100-15, Session 3

Efficient extreme up-conversion through steady-state non-thermal-equilibrium excitation

Shimry Haviv, Dafna Granot, Nimrod Kruger, Assaf Manor, Tamilarasan Sabapathy, Carmel Rotschild, Technion-Israel Institute of Technology (Israel)

Frequency up-conversion is a technique for the generation of high energy photon from two or more lower energy photons. Although many up-conversion techniques have been demonstrated such as parametric up-conversion or multi-photon absorption, their conversion efficiencies become negligible for high-order up-conversion. Alternatively, in thermal emission very high temperatures are needed for reasonable efficiencies and the emission is spectrally broad rendering this up-conversion method impractical for most applications. We present a new efficient extreme up-conversion method for generating NIR and visible wavelengths using CW LWIR laser by non-thermal-equilibrium excitation through spontaneous reduction of the chemical potential. In this method we exploit the high chemical potential of the pump specific modes to excite the vibronic states of the host, subsequently transferring the energy to chosen emitters, resulting in narrow non-thermal steady-state emission. All while, only residual energy contributes to material's temperature, thus keeping it at a comparably low temperature. We experimentally demonstrate 7, 10, 13, 16, and 20-fold up-conversion at external efficiency of up to 4%, exceeding black-body radiation of the bulk temperature. Furthermore, we present energy transfer between emitters, a phenomenon in contrast to thermal emission, showing the photoluminescence behavior of this method. We use CW CO2 laser (10.6?m) to excite silica vibronic states and transfer the energy to rare-earth emitters at the NIR and visible spectrum. This new outlook on up-conversion via energy transfer paves the way for developing new light sources and new methods of imaging and detection with high efficiencies.

10100-16, Session 4

Electro-optic KTN deflector stabilized with 405-nm light irradiation for wavelength-swept light source

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We have developed a highly stable electro-optic potassium tantalate niobate (KTa1-xNbxO3, KTN) deflector by enhancing electron transportation through KTN crystal. A KTN deflector has been reported as a promising high-speed (200 kHz) wavelength selective device in a swept source optical coherence tomography light source with high phase stability. Despite the fast EO response of up to several hundred MHz, deflection angle drift limits long-term operation. The main reason is considered to be the gradual change in trapped electron density inside the KTN crystal. The trapped electrons must be in a steady state because they are used to build up the refractive index distribution to deflect the optical beam. We irradiated 405-nm light during an optical beam scan to rapidly induce a stable refractive-index change. The measured current increase under 405-nm light irradiation and an applied voltage implies that trapped electrons are partially excited to the conduction band. Thus the improved free-carrier density enables trapped electrons to rapidly reach an equilibrium state. The deflection angle was set at 160 mrad within several ten seconds and remained at this angle for over a month when the 1300-nm laser light was scanned continuously at a repetition rate of 20 kHz. Moreover, we confirmed that the deflection angle is adjustable with our method. The developed deflector has been applied to a wavelength-swept light source for measuring the thickness of 3.6 mm-optical-length Si wafers. 0.1-μm precision was achieved continuously corresponding to the stability of the KTN deflector.

10100-17, Session 4

An ultrafast optical shutter exploiting total light absorption in a phase change material

Mohsen Jafari, L. Jay Guo, Mina Rais-Zadeh, Univ. of Michigan (United States)

In this paper, we present an ultra-fast and high-contrast optical shutter with applications in atomic clock assemblies, integrated photonic systems, communication, etc. The shutter design exploits the total light absorption phenomenon in a thin phase change (PC) material placed over a metal layer. ON/OFF states of the shutter is achieved by the change of the refractive index of the PC material in its two stable states. The PC material used in this work is Germanium Telluride (GeTe), a group IV-VI chalcogenide compound, which demonstrates good optical contrast when switching from amorphous to crystalline state and vice versa. The phase changing behavior and reliability of GeTe and GeSbTe (GST) have been verified in optical memories and RF switches. Here, GeTe is used as it has a low extinction coefficient in near-IR regions and can be thermally transitioned between two phases by applying electrical pulses to an integrated heater. Memory behavior of GeTe results in zero static power consumption. We previously demonstrated a meta-surface employing GeTe in sub-wavelength slits with > 14dB isolation at 1550nm by exciting the surface plasmon polariton and localized slit resonances. In this work, strong interference effect in a thin layer of GeTe over a gold mirror results in near total light absorption of up to 40dB in the amorphous phase of the shutter at 780nm. The optical loss at the shutter ON state is less than 1.5dB. A NiCr heater provides the Joule heating energy required to achieve the crystallographic phase change. The switching speed is ~2us.

10100-18, Session 4

Enhancing human color vision with thin-film optical filters by breaking binocular redundancy

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Human color vision relies on three types of photosensitive cone cells in the retina, which the brain integrates to determine the perceived color of an object. Though this system works well, it discards a large amount of information by compressing the spectrum of each region in the visual field into three color channels.

We set out to enhance human color vision by decreasing the amount of spectral information that is discarded. Our approach focuses on breaking the redundancy of the two eyes, which typically have the same color sensitivity and field of view, by providing different spectral content to each eye.

We designed spectacles comprising two distinct transmission filters, one for each eye, which enhance the ability to perceive color. These filters are designed using a psychophysical model that predicts the perceived color of a given spectrum, and utilizes optimization methods to generate a thin-film stack. The design constraints ensure that the transmission response of the two filters are sufficiently distinct, while enforcing a white-balance condition to prevent clashing between the two eyes.

We fabricated and tested a design that "splits" the response of the short-wavelength cone, effectively creating four cone types between the two eyes. Users of our spectacles were able to differentiate between various blue, purple, and violet metamers (pairs of distinct spectra that resolve to the same perceived color), without adverse secondary effects to vision. Potential applications include camouflage detection, color-blindness treatment, anti-counterfeiting, and quality control.

10100-20, Session 4

Long-range automotive LiDAR with silicon photomultipliers

Carl Jackson, Salvatore Gnecchi, Edel Cashman, Steve Buckley, Stephen J. Bellis, SensL Technologies Ltd. (Ireland)

LiDAR has become a critical requirement for Advanved Driver Assistance Systems (ADAS) as the automotive industry moves towards improved driver safety and autonomous cars. Silicon Photomultipliers (SiPM) and Single Photon Avalanche Diodes (SPAD) sensors are emerging as the most promising sensor technology for long range, >100m, direct time-of-flight LiDAR that needs to function in bright daylight and with low reflectance targets.

SensL is developing a new range of SiPM, the R-Series, that have improved detection efficiency at longer wavelengths used in LiDAR. In parallel to the sensor development, SensL is working to understand the fundamental advantages SiPM and SPAD sensor arrays provide long-range, ADAS LiDAR systems.

It will be shown that to achieve long range LiDAR with eye-safe lasers, a sensor with single photon sensitivity is required. This is due to the low number of returned photons from distances greater than 100m. When ambient daylight conditions are taken into account, the small returned signal at these distances can be easily lost in the noise and histogramming multiple laser pulses will be shown to provide the only method which allows for accurate time of flight ranging operation.

The histogramming technique and the architecture used to implement it will be described. A portable long-range LiDAR demonstrator using SiPM sensors has been developed and will be presented including range accuracy versus distance and low reflective targets. This will be compared to a detailed Monte Carlo model which will be shown to accurately describes SiPM and SPAD array operation in LiDAR ranging.

10100-21, Session 4

Sidelobe considerations in AOTF imaging

Neelam Gupta, U.S. Army Research Lab. (United States); Dennis Suhre, DRS Scientific Inc. (United States)

An acousto-optic tunable filter (AOTF) is an all solid-state no-moving parts robust device that has been used in the development of hyperspectral imagers from the ultraviolet to the longwave infrared. Such a device is fabricated by bonding a piezoelectric transducer on a specially cut birefringent crystal prism. When broadband unpolarized light is incident on the AOTF, two orthogonally polarized diffracted beams at a wavelength with a narrowband bandpass are transmitted. The diffracted wavelength depends upon the applied RF and the prism parameters and can be tuned by varying the applied RF which is useful for hyperspectral imaging applications. The spectral response of an AOTF is narrowband and depends on the AOTF design and has sidelobes that are usually not considered in the hyperspectral imaging applications. When imaging is carried out for a scene with a laser present, the spectral images do get affected by these sidelobes. We have carried out a detailed study of sidelobes of a TeO_2 AOTF operating from 0.9 to 1.7 micron using a laser and a broadband source with an InGaAs camera. A 16-channel RF driver was used to control both the amplitude and frequency. By applying specific RF signals to the AOTF, we measured the detailed sidelobe structure for the AOTF by analyzing the spectral response and compared it with theory. The AOTF imaging system used a telecentric confocal optics that compensates for the AOTF aberrations, which are severe at high sidelobe operation. We will discuss experimental setup and present both experimental and theoretical results.

10100-22, Session 4

Three types of immersed grating for next-generation infrared spectrometer

Takashi Sukegawa, Yukinobu Okura, Canon Inc. (Japan)

Since Immersed grating provides n (refractive index of its material) times higher spectral resolution compared to a conventional reflective grating of the same size, Immersed grating is a powerful optical device for the infrared high-resolution spectroscopy. Recently a high-resolution spectroscopy in the infrared wavelength range is increasing the importance increasingly for observations of relating with H_2O, NHx, NOx and organic molecules. Higher spectral resolution allows us to detect weak lines without spectral line confusion. On the other hands, there is no practical immersed grating for high-resolution spectroscopy except Si immersed grating by anisotropic etching. It was very difficult for a fragile IR crystal to manufacture a diffraction grating precisely by machining. Our original free-forming machine has accuracy of a few nano-meter in positioning and stability. We succeeded in fabricating immersed gratings with three kinds of materials. Three materials are CdZnTe, germanium and InP, each refractive index are about 2.6,4 and 3.1 respectively. By combining these devices, a spectroscopy with immersed grating is realizable in the wavelength range of 1.5-20um. Thereby, the realization of these immersed gratings has led to a dramatic improvement in the operability and performance of next generation high-performance spectroscopy. In this paper, we report performance of our immersion gratings and other possibility.

10100-23, Session 5

Liquid polymeric materials for optical nano-bio sensing *(Invited Paper)*

Euan McLeod, The Univ. of Arizona (United States)

In this invited talk, we present our work on developing liquid polymeric nanofilms and nanodroplets to aid in the detection of nanoparticles and viruses using cost-effective and field-portable lensfree on-chip holographic microscopy. The sizing of individual nanoparticles and the recovery of the distributions of sizes from populations of nanoparticles provide valuable information in a variety of fields, including virology, exosome analysis, air and water quality monitoring, homeland security, and nanomaterials synthesis. Conventional approaches for nanoparticle sizing include those based on costly and low-throughput laboratory-scale equipment such as transmission electron microscopy or nanoparticle tracking analysis, as well as those approaches that only provide population-averaged quantities, such as dynamic light scattering. Here we overcome these limitations by combining lensfree holographic on-chip microscopy with the self-assembly of liquid polyethylene glycol (PEG) nanolenses around target nanoparticles adsorbed on a glass substrate. The nanolenses can be self-assembled by several different mechanisms, including flow-based formation, condensation of a thin film from PEG vapor, and condensation of PEG droplets from vapor. The mechanisms behind these morphologies as well as their relative performance will be presented. Experimental results show that more than 10^5 individual nanoparticles as small as 40 nm can be detected and sized with accuracy +/- 11 nm. These approaches are amenable to a large dynamic range of particle sizes (40 nm – 100s of microns) and can accurately size multi-modal distributions of particles. Instances of this approach have been implemented in compact and cost-effective devices suitable for use in the field and/or in low-resource settings.

10100-24, Session 5

Fiber-optic current sensor with high sensitivity using a microfiber loop resonator

Seung Min Lee, Jong Cheol Shin, Ju Il Hwang, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

The optical resonators based on microfiber are very sensitive to a change in the surrounding environment due to the large evanescent field in the microfiber. Recently, the current sensor based on microfiber knot resonator (MKR) has been reported. The current sensor based on MKR was able to overcome the limitation of previous optical current sensor such as, requirement of very long length of fiber due to extremely a small Verdet constant of silica and the complex manufacturing techniques to coat the fiber. However, it is not easy to improve the current sensitivity of the MKR-based current sensor with a copper support rod because of the low the low value of thermal-expansion coefficient and electric resistivity of the copper wire and an undesirable insertion loss in the interface between the copper rod and the MKR.

In this paper, we propose a highly sensitive current sensor based on a microfiber loop resonator (MLR) incorporating low index polymer. A microfiber with a diameter of 1 ?m is coiled around a nichrome wire with low index polymer coating to make a MLR around the nichrome wire. The electric current in the nichrome wire increases temperature around the nichrome wire and accordingly changes thermal properties of the MRL and low index polymer. Therefore, the proposed MLR-based current sensing probe incorporating low index polymer has a high current sensitivity of 437.9 pm/A^2, which is ~10 time higher than the previous result.

10100-25, Session 5

Fiber Bragg grating regeneration modeling and ultra-wide temperature sensing application

Lin Lu, BeiHang Univ. (China); Yuanhong Yang, BeiHang Univ (China); Mingming Zheng, BeiHang Univ. (China); Wei Jin, The Hong Kong Polytechnic Univ. (China)

Three types of Fiber Bragg gratings (FBGs) were inscribed in both H2-loaded and H2-free fiber with phase mask using 800nm femtosecond (fs) laser, 244nm Ar+ laser, respectively. The reflection spectrum regeneration phenomenon of these FBGs were observed under different high annealing temperatures. The models of regeneration process as well as regeneration temperature and time have been established based on the temperature annealing experiment results. The FBGs regeneration temperature threshold has been defined and investigated. Experimental results and model study show that the regeneration temperature threshold of fs FBG written in H2-free fiber, fs FBG written in H2-loaded fiber and UV FBG in H2-loaded fiber are around 888?, 780? and 770? respectively. The regenerated FBGs in H2-loaded fiber decay in case of high temperature, while regenerated fs FBG in H2-free fiber have excellent high temperature stability. The temperature sensing characteristic of the three types of FBGs were investigated and compared experimentally under ultra-wide temperature range (-196? ~ 1200?) with liquid nitrogen canister and high temperature tube furnace. And the long time (more than 12 hours) high temperature stability was performed meanwhile. The experimental results show these FBGs can all operated within this ultra-wide temperature range. But the regenerated FBGs in H2-loaded fiber decay in case of high temperature, while regenerated fs FBG in H2-free fiber have best stability and higher temperature sensitivity coefficient in all regenerated FBGs was obtained.

10100-26, Session 5

Rare-earth-doped chalcogenide glasses for mid-IR gas sensor applications

Julien Ari, Institut des Sciences Chimiques de Rennes (France) and Ctr. d'Optique, Photonique et Laser (Canada); Florent Starecki, Catherine Boussard-Plédel, Institut des Sciences Chimiques de Rennes (France); Jean-Louis Doualan, Ctr. de Recherche sur les Ions, les Matériaux et la Photonique (France); Lionel Quétel, IDIL Fibres Optiques (France); Karine Michel, Bureau de Recherches Géologiques & Minières (France); Alain Braud, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); Patrice Camy, Ctr. de Recherche sur les Ions, les Matériaux et la Photonique (France); Radwan Chahal, Institut des Sciences Chimiques de Rennes (France); Bruno Bureau, Institut des Sciences Chimiques de Rennes (France); Yannick Ledemi, Younès Messaddeq, Ctr. d'Optique, Photonique et Laser (Canada); Virginie Nazabal, Institut des Sciences Chimiques de Rennes (France)

Chalcogenide glasses have a high potential for infrared applications using their optical properties. These materials can be embedded in optical sensors through their good light transmission up to 25 µm, who allows us to detect infrared signatures of all molecules with absorption bands in this spectral region. Selenium and sulfur based glasses have a relatively good solubility for rare-earth ions in the glass host. Moreover, these materials provide a low phonon energy (~ 200 cm-1 for selenide and ~ 335 cm-1 for sulfide glasses), that induces less non-radiative relaxation and gives a better fluorescence efficiency. That's why they are suitable for fiber laser applications and mid-IR gas sensors. We use these fibers doped with rare-earth ions as a light

mid-IR source and integrate them in an environmental sensor for its ability to detect greenhouse gas who have an infrared absorption band in this spectral range, such as CO2.

Luminescence properties of Pr3+, Dy3+ and Er3+ doped GaGeSbSe(S) systems has been studied. The synthesis process to obtain homogeneous glasses has been determined and fibers has been successfully drawn and characterized from these preforms. Fibers show a mid-IR luminescence matching with the CO2 absorption band at 4.3 μm and can be used in an environmental monitoring sensor for the CO2 storage underground. The luminescence and glasses properties have been investigated on bulk samples and fibers in order to improve the efficiency of an optical CO2 prototype sensor from high to low concentration, down to the ppm level.

10100-27, Session 5

Upconversion emission of erbium-doped lanthanum oxysulfide powders for temperature sensing

Rolindes Balda, Univ. del País Vasco (Spain) and Consejo Superior de Investigaciones Científicas (Spain); Noha Hakmeh, Odile Merdrignac-Conanec, Univ. de Rennes 1 (France); Maria Angeles Arriandiaga, Univ. del País Vasco (Spain); Joaquin Fernandez, Univ. del País Vasco (Spain) and Ctr. de Fisica de Materiales (Spain)

Frequency upconversion of infrared (IR) into visible (VIS) light in rare-earth (RE) doped solids has attracted much interest because of its large number of potential applications in several areas such as color displays, upconversion lasers, IR detection, sensors, and others. One of the requirements for efficient upconversion is the low phonon energy of the host matrix. Though fluoride compounds have been extensively studied due to their low phonon energy, chloride- and sulfide-based hosts present the advantage of a lower phonon energy that leads to a significant reduction of the multiphonon relaxation rates. The low phonon maximum energy (? 400 cm-1) lanthanum oxysulfide crystal is a wide-gap semiconductor material known as an excellent host for trivalent rare-earth ions.

In this work we report a detailed spectroscopic study of the near-infrared to visible upconversion luminescence in Er-doped lanthanum oxysulfide crystal powders following excitation into the 4I9/2 level. The analysis of the upconversion emission and excitation spectra as well as the decay curves indicates that energy transfer upconversion is the main mechanism responsible for the green (4S3/2) and red (4F9/2) upconversion luminescence. The temperature dependence of the green upconverted emission from the two thermally coupled 2H11/2 and 4S3/2 levels has been analyzed in the 240 K- 300 K temperature range in order to check its availability as a temperature sensor.

10100-28, Session 5

Optimized design of a nanocomposite Ta2O5 and Pd multilayer OFSPR H2 sensor: a theoretical analysis

Fionn Downes, Cian M. Taylor, Institute of Technology Sligo (Ireland)

The application of hydrogen as a clean renewable source of fuel is central in advancing towards a sustainable society. The extremely dangerous nature of such an energy source necessitates continued advances in sensing technology.

Excellent sensing performance has been demonstrated using a multilayer OFSPR H2 sensor [1]. Hosoki et al. have demonstrated experimental success employing Ta2O5 as a modulation layer in their Pd-based OFSPR hydrogen sensor [2], which operated with improved sensitivity as compared to the more widely used SiO2. There is now growing interest in the use of nanocomposite materials in the multilayer [3]. Improved hydrogen sensing performance has been reported, a nanocomposite consisting of Pd nanoparticles in a host matrix of ZnO [4].

In this submission, we perform a theoretical investigation into the performance of a novel multilayer sensing structure containing Ag as the SPR-supporting metallic layer along with a nanocomposite of Ta2O5 and Pd. We compare the performance of this novel sensor in terms of sensitivity and detection accuracy to the standard individual multilayer sensing structure Ag/Ta2O5/Pd. We find that the nanocomposite structure operates with significantly improved performance as compared to the standard individual multilayer structure under certain design parameters. We identify the key factors that influence performance including metallic thickness, nanocomposite thickness, and the volume fraction of Pd. Finally, we demonstrate a method by which the sensor can be optimized corresponding to the wavelength of the sensing light source.

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10100-29, Session 6

Integrated optic waveguides in gallium lanthanum sulfide glass for mid-IR applications

Jesse A. Frantz, Jason D. Myers, L. Brandon Shaw, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States)

Chalcogenide integrated optic waveguides operating in the mid-wave infrared (MWIR) are of interest for a variety of applications. They are potentially useful in compact MWIR laser sources for applications such as gas sensing and infrared countermeasures. Most work on chalcogenide integrated optics to date, however, has focused on arsenic sulfide, As2S3, or glasses with similar compositions. These glasses are known to suffer from a host of photo-induced effects including photo-darkening, photo-induced crystallization, and low optical damage thresholds. Furthermore, they can typically accept only low concentration of rare earth dopants without clustering or crystallization. Gallium lanthanum sulfide (GLS) is an alternative chalcogenide glass with great potential for use in integrated optics devices operating in the MWIR. Like As2S3, GLS exhibits a large transparency window in the MWIR and high optical nonlinearity, but it does not suffer from the same type of photo-induced effects. High RE dopant concentrations without clustering are possible in GLS because rare earth ions substitute for lanthanum ions in the glass matrix. Integrated optic waveguides have previously been fabricated in GLS by several methods. Formerly, it was hypothesized that patterning GLS via reactive ion etching (RIE) was impossible do the presence of lanthanum and rare earth dopant ions, but we present results for GLS waveguides fabricated via RIE. In addition, we demonstrate 2.7 ?m emission from Er(3+)-doped GLS waveguides resulting from erbium's 4I(11/2)?4I(13/2) transition.

10100-30, Session 6

High-power and -efficiency clad-pumped Er:YAG planar waveguide laser

Nikolay E. Ter-Gabrielyan, Viktor Fromzel, U.S. Army Research Lab. (United States); Helmuth E. Meissner, Stephanie K. Meissner, Onyx Optics Inc. (United States); Mark Dubinskii, US Army Research Lab (United States)

Crystalline waveguide lasers are very attractive as efficient and compact high power laser sources due to their ability to provide high pump intensity and tight confinement of the pump and laser modes along the entire length of the gain medium, which can be 5-10 times longer than that in conventional bulk solid state lasers. Reported here is an efficient CW laser operation of a 200 mm long Er:YAG planar waveguide (PWG) resonantly cladding-pumped by a laser diode bar stack at 1532 nm. A diffusion bonded PWG had a rectangular 1% Er:YAG core, cross section 4 mm x 50 um (NA core = 0.02), surrounded by a modified YAG cladding, cross section 4 mm x 1 mm (NA clad = 0.55). Laser diode bar stack power was focused so as to fill the entire cladding cross section. The waveguide was conductively cooled through the sapphire substrate-plate (in a function of a TEC-matching structure rigidizer) diffusion bonded to the bottom of the waveguide, which was, in turn, mounted on a water-cooled copper heatsink. A CW output power of 75 W at 1645 nm has been achieved in our experiments with the slope efficiency of 64%. To the best of our knowledge, this is the highest power and efficiency ever reported from Er-doped planar waveguide laser.

10100-32, Session 6

Waveguide structures in anisotropic nonlinear crystals

Da Li, Helmuth E. Meissner, Pengda Hong, Stephanie K. Meissner, David Meissner, Onyx Optics Inc. (United States)

Onyx Optics presents the design and manufacturing parameters of waveguiding structures of anisotropic nonlinear crystals that are employed for harmonic conversions, using Adhesive-Free Bonding (AFB®). This technology enables a full range of predetermined refractive index differences that are essential for the design of single mode propagation with high efficiency in anisotropic nonlinear crystals which in turn results in compact frequency conversion systems. Examples of nonlinear optical waveguides include periodically bonded walk-off corrected nonlinear optical waveguides and periodically poled waveguide components, such as lithium tetra-borate (LBO), beta barium borate (?-BBO), lithium niobate (LN), potassium titanyl phosphate (KTP), zinc germanium phosphide (ZGP) and silver selenogallate (AGSE). Simulation of planar LN waveguide shows that when the electric field vector E lies in the k-c plane, the power flow is directed precisely along the propagation direction, demonstrating waveguiding effect in the planar waveguide.

Employment of anisotropic nonlinear optical waveguides, for example in combination with AFB® crystalline fiber waveguides (CFW), provides access to the design of a number of novel high power and high efficiency light sources spanning the range of wavelengths from deep ultraviolet (as short as ~200 nm) to mid-infrared (as long as about 18 μm). To our knowledge, the technique is the only generally applicable one because most often there are no compatible cladding crystals available to nonlinear optical cores, especially not with an engineer-able refractive index difference and large mode area.

10100-33, Session 6

Characterization of waveguide structures produced by femtosecond pulse laser in transparent polycrystalline ceramics

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While ceramics offer high temperature, chemical stability and relatively efficient fabrication compared to glasses and single crystals, a drawback to the widespread application of waveguide structures in ceramic-based devices is the relatively high power that is necessary to induce permanent optical changes in ceramics. We detail a process to induce waveguide structures into transparent polycrystalline ceramics using femtosecond laser pulses of only a few nJ. These waveguides are characterized for reflection, coupling, and propagation losses through straight and various curved sections to determine the change in refractive index. The number of passes with the laser (i.e., total incident pulses per unit area) was found to affect the waveguide writing. The optical properties of our Current Activated Pressure Assisted Densification (CAPAD) ceramics are discussed. The samples are prepared from powders of various nanometer size and were not annealed after CAPAD. The transmittance of Yttria Stabilized Zirconia ceramics increases with increasing wavelengths, suggesting that the transmittance of the waveguide structures should be higher at higher wavelengths. This opens the possibility for the use of this material in telecommunications applications. The waveguide-like structures are most likely the result of regions where the concentration of oxygen vacancies and/or their associated free electrons have been altered by laser irradiation. Our findings forecast increased attention on transparent polycrystalline ceramics for optical applications such as laser source materials, solid state lighting and light manipulation.

10100-34, Session 7

Infrared glass-based negative-curvature anti-resonant fibers fabricated through extrusion

Rafael R. Gattass, U.S. Naval Research Lab. (United States); Daniel L. Rhonehouse, Univ. Research Foundation (United States); Daniel J. Gibson, U.S. Naval Research Lab. (United States); Collin McClain, Sotera Defense Solutions (United States); Rajesh Thapa, Sotera Defense Solutions, Inc. (United States); Vinh Q. Nguyen, Shyam S. Bayya, L. Brandon Shaw, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States); R. Joseph Weiblen, Curtis R. Menyuk, Univ. of Maryland, Baltimore County (United States)

Negative curvature fibers have been gaining attention as fibers for high power infrared light. Currently, these fibers have been made of silica glass and infrared glasses solely through stack and draw. Infrared glasses' lower softening point presents the opportunity to perform low-temperature processing methods such as direct extrusion of pre-forms. We demonstrate an infrared-glass based negative curvature fiber fabricated through extrusion. The fiber shows record low losses in 9.75 – 10.5 μm range (which overlaps with the CO_2 emission bands). We show the fiber's lowest order mode and measure the numerical aperture in the longwave infrared transmission band. The possibility to directly extrude a negative curvature

fiber with no penalties in losses is a strong motivation to think beyond the limitations of stack-and-draw to novel shapes for negative curvature fibers.

10100-35, Session 7

Direct writing of ferroelectric crystalline structures in glass

Carl M. Liebig, Jonathan T. Goldstein, Air Force Research Lab. (United States); Sean McDaniel, Air Force Research Lab. (United States) and Leidos (United States); Carl Cook, Air Force Research Lab. (United States)

Noncentrosymetric crystals (NCCs) are of significant interest to the optical community as a lack of inversion symmetry is required for second order nonlinear electro-optical applications such as second harmonic generation (SHG). Recently a crystal growth technique has been demonstrated where high repetition rate femtosecond lasers were used to precipitate aligned single crystalline NCCs within supersaturated glasses. An advantage to laser writing of NCCs in glass is the alignment of the polar axis along the inscription direction. Femtosecond precipitation of NCCs in glass has the potential to be a lower-cost alternative to other methods of growing NCC structures. In this study Lithium Niobate, a widely used electrooptic crystal, was precipitated in 33LiO2-33Nb2O5-34SiO2 (mol%) (LNS) glass, forming aligned crystalline structures within an amorphous matrix. The precipitated lithium niobate was characterized, and structure determined, and orientation measured. The crystalline characteristics of the LiNbO3 were measured to determine the optimal writing conditions for obtaining aligned crystalline structures. This procedure was modified to functionalize the precipitated crystals for photonic applications.

10100-36, Session 7

Fusion splicing of highly dissimilar single crystal YAG fiber and silica fiber

Rajesh Thapa, U.S. Naval Research Lab. (United States) and Sotera Defense Solutions, Inc. (United States); Daniel J. Gibson, Rafael R. Gattass, Woohong Kim, Shyam S. Bayya, L. Brandon Shaw, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States)

Splices between materials with dissimilar thermal expansion and melting points are particularly difficult to create. We have developed a method for splicing YAG single crystal fiber to silica fiber. The YAG fiber used here is a 100 µm single crystal core-only fiber with no cladding. The fiber is doped with Yb3+, for lasing and gain at a wavelength of around 1030 nm. Optical losses associated with the splices were measured for multimode fibers to be 0.33 dB. The silica-YAG splice was tested to the maximum applied static load of the instrument, more than 400 g of tension in the direction of the fibers axes before fracturing which is more than 50 kpsi of tensile strength for the 100 ?m diameter fiber. To better understand the bonding mechanism behind the strength of the splice, electron probe microanalysis (EPMA, JEOL Superproble 733) was performed to measure the elemental profile across the spliced-region. Study of the elemental composition at the splice interface showed formation of a stable intermediate material that provides mechanical strength to the splice. The existence of low melting ternary eutectic and reaction points enables the co-melting of YAG and silica at a temperature (~1350°C) much lower than the melting points of the individual fibers and allows for robust fusion splicing of these dissimilar fibers. While the elemental composition of the interface material was measured, the specific phases present, i.e. the crystalline or amorphous nature of the material was not determined and is an area of interest for future study. This is a major step toward developing very high power integrated and compact laser systems based on crystals and glass despite their stark dissimilarities in physical and material properties.

10100-37, Session 7

Novel optical technique for 2D graphene reduction

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Scaling from lab technology to industrial level of graphene requires the establishment of novel development and conjugation of processing methods and procedures which exceed current industrial practice.

Non-linear interaction between photons and carbon bonds not only provides the possibility to design unique photonic devices but also opens the route for laser-based graphene processing. Interaction of graphene lattice and pulsed laser irradiation in different environmental conditions can produce etching and ablation, reduction, oxidation, growth, etc., with resolution down to the nanoscale, turning the laser processing in one of the most attractive tools for graphene device manufacturing.

Methods for reducing graphite oxide have included high-temperature annealing under chemical reducing gases and/or inert atmospheres, flash reduction chemical reduction via various reducing agents, solvothermal reduction, a combination of chemical and thermal reduction methods, and most recently, laser reduction of GO.

The idea of totally mask-free processing of graphene is also attractive to improve flexibility, reduce costs, and reduce alignment operations, by producing fully functional instruments in single direct-write operations. But, it is still challenging to achieve a single-step laser processing for controlled and dependable chemical functionalization of graphene, and a large set of uncontrolled variables play a major role.

Laser scribed graphene is shown to be successfully produced and selectively patterned from the direct laser irradiation of graphite oxide films under ambient conditions. In addition, by varying the laser intensity, power, and laser irradiation treatments, the electrical properties of LSG can be accurately attune over 5 orders of magnitude of conductivity, a feature that has proven difficulty with other methods.

10100-38, Session 7

Thermal conductivity investigation and power scaling of adhesive-free bond laser components

Da Li, Onyx Optics, Inc (United States); Helmuth E. Meissner, Pengda Hong, Stephanie K. Meissner, David Meissner, Onyx Optics Inc. (United States)

An interferometric method has been developed at Onyx Optics, Inc. to accurately measure the thermal conductivity and heat transfer resistance at the interface of adhesive-free bond (AFB®) laser composites. Single crystal bars and AFB bonded crystal doublets with the combinations of various rare-earth (Nd3+, Yb3+, Er3+, Tm3+, and Ho3+) trivalent ion doped YAG, and un-doped YAG have been fabricated with AFB technique. By loading the test sample in a vacuum cryostat, with a precisely controlled heat load at one end of the doublets, the temperature distribution inside the single crystal or the composite samples can been precisely mapped by measuring the optical path difference interferometrically, given the material's thermal-optical properties. No measurable heat transfer resistance can be identified for the AFB interfaces between low-concentration doped YAG and un-doped YAG. For the heavily doped RE3+:YAG, for example, 10% Yb:YAG, the thermal conductivity measured in our experiment is 9.1 W/m*K, using the

thermal conductivity of undoped YAG reported in [1] as basis. The thermal transfer resistance of the AFB interface with un-doped YAG, if there is any at the AFB interface, could be less than 2.1*10^-6 m^2*K/W.

The measured thermal conductivity for various RE3+:YAG is applied to Dawson's model [2] for power scaling of double-clad crystal fiber (CFW). Hard upper limits of CFWs are estimated with selected core/inner cladding material, where the output is intrinsically single transverse mode.

10100-39, Session 8

Non linear glasses-based microstructured or step-index optical fibers: mid-IR supercontinuum generation and IR spectroscopy applications *(Invited Paper)*

Frédéric Smektala, Bertrand Kibler, Clément Strutynski, Jérémy Picot-Clémente, Arnaud Lemière, Paul Froidevaux, Frédéric Désévédavy, Grégory Gadret, Jean-Charles Jules, CNRS-Université de Bourgogne Franche Comté (France)

No Abstract Available

10100-41, Session 8

IR-transmitting GRIN chalcogenide optics

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Graded index (GRIN) optical materials and novel lens offer numerous benefits for infrared applications, where selection of conventional materials is limited. For optical systems that must perform over wide spectral regions, the reduction of size weight and complexity can be achieved through the use of GRIN elements. At the Naval Research Laboratory (NRL) we are developing new technologies for IR gradient index (IR-GRIN) optical materials. This paper will present the latest progress in the development of these materials including their design space guidelines, fabrication, metrology, optics characterization, and preliminary imaging demonstration.

10100-42, Session 8

IR optics of chalcogenide glasses made by mechanical alloying and sintering *(Invited Paper)*

Laurent Calvez, Xiang-Hua Zhang, Anna Novikova, Jean Luc Adam, Univ. de Rennes 1 (France)

Chalcogenide glasses are widely used for infrared applications. The presence of oxygen during their synthesis process leads to the presence of detrimental absorption bands on the transmission spectra. To avoid this phenomenon, these glasses are synthesized using expensive and single use silica tubes sealed under vacuum. The low thermal conductivity of silica also limits the quenching rate, and thus the size of the samples produced. In this study, we present a new synthesis way to make chalcogenide glasses and glass-ceramics without the use of silica tubes. An amorphous powder of the GeSe4 and 80GeSe2-20Ga2Se3 glasses is produced by mechanical milling of the raw starting elements (Ge, Ga, Se) and is then sintered using Spark Plasma Sintering (SPS) technique or under complex shape by hot pressing. Bulk glasses and glass-ceramics with higher dimensions and transparent in the infrared region were produced [1, 2]. This process paves the way of a novel approach for the production of chalcogenide glasses and glass-ceramics for infrared applications at a lower cost. We have also demonstrated the possibility to apply this technique for various glass compositions such as Te-As-Se, Ge-Sb-Se, Ge-Ga-Te...

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10100-43, Session 8

New IR materials for multispectral optics

Shyam S. Bayya, Daniel J. Gibson, Vinh Q. Nguyen, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States); Mikhail Kotov, Sotera Defense Solutions, Inc. (United States); John P. Deegan, George P. Lindberg, Blair L. Unger, Rochester Precision Optics, LLC (United States)

There is a strong desire to reduce size and weight of single and multiband IR imaging systems in ISR operations on hand-held, helmet mounted or airborne platforms. Current systems are limited by bulky optics. We have recently developed a large number of new optical materials based on chalcogenide glasses which transmit in SWIR to LWIR wavelength region that fill up the glass map for multispectral optics and vary in refractive index from 2.38 to 3.17. They show a large spread in dispersion (Abbe number) and offer some unique solutions for multispectral optics designs. These glasses were specifically designed to have comparable glass molding temperatures and thermal properties to be able to laminate and co-mold the optics and reduce the number of air-glass interfaces (lower Fresnel reflection losses). These new NRL glasses also have negative or very low positive dn/dT making it easier to athermalize the optical system. This presentation will cover discussions on the new optical materials, multispectral designs, fabrication and characterization of new optics.

10100-44, Session 8

IRG27: a new glass type for multi-band IR optics

Mark J. Davis, William James, SCHOTT North America, Inc. (United States)

SCHOTT has developed a series of new chalcogenide glasses which offer improved transmission at short wavelengths, reduced dn/dT and tailored dispersion for multi-band applications from NIR through LWIR. The new glass type IRG27, which has near-zero dn/dT and is particularly well suited for SWIR and MWIR, will be introduced and discussed in the context of materials selection for multi-band and broadband infrared applications

10100-45, Session 9

Temperature dependence of gain in a highly-stacked quantum-dot semiconductor optical amplifiier

Naoya Yoshida, Aoyama Gakuin Univ. (Japan); Kouichi Akahane, Naokatsu Yamamoto, Atsushi Matsumoto, National Institute of Information and Communications Technology (Japan); Hideyuki Sotobayashi, Aoyama Gakuin Univ. (Japan)

We investigated the temperature characteristics of a modularized

semiconductor optical amplifier (SOA) utilizing InAs/AlGaAs quantum dot (QD) in the active layer operating at C-band (1.53μm–1.56μm). It has been reported by many literatures on physics that QDs are superior at energy efficiency and leads to less thermal energy generation. By changing the inner temperature of the module from 20? to 80?, we measured the difference in the gain at each input power and injection current. The QD-SOA we measured was utilizing InAs QD in active layer and the laminated structure had 20 layers having 20nm of intermediate layers which refers to the width between QDs. When the input power was -50 dBm, we successfully confirmed more than 10 dB at the inner temperature of 70? by injecting a current larger than 400 mA. In addition, we obtained a maximum gain of 20.68 dB at the center wavelength and a constant gain of approximately 15 dB at other inner temperatures. It can be concluded from the output of the experiment that this QD-SOA can be put to use in optical communication in several situations where the inner temperature ranges between 20? to 80?. This involves a new approach towards the application of QD amplifiers in the field of optical fiber communications.

10100-46, Session 9

633-nm single-mode laser diode module with PM fiber output

Gunnar Blume, Daniel Jedrzejczyk, Johannes Pohl, David Feise, Alexander Sahm, Ferdinand-Braun-Institut (Germany); Christian Nöllecke, Patrick Leisching, TOPTICA Photonics AG (Germany); Katrin Paschke, Ferdinand-Braun-Institut (Germany)

The helium-neon laser emitting at 633 nm is still widely used in the fields of holography and metrology. While this laser offers an excellent beam quality and a long coherence length, several fundamental properties, such as the size and the requirement for a high-voltage supply, make it unsuitable for many applications.

Semiconductor-based diode lasers are promising candidates to overcome these limitations. However, diode lasers pose their own challenges. The broad gain spectrum requires suitable mode filtering, the astigmatic beam has to be adapted to a single-mode fiber, and the low resonator finesse requires protection from feedback. In order to tackle these challenges we developed a compact package with integrated beam shaping, optical isolation and fiber coupling.

The 633 nm laser diode is based on an AlGaAs/AlGaInP structure and was grown by MOCVD on GaAs substrates. It features a ridge waveguide with a width of 5 μm and a 10th order DBR surface grating at the rear side. The diode laser emits about 11 mW at a temperature of 20°C and a current of 100 mA. The beam is shaped with two cylindrical micro-lenses to obtain an almost circular beam and passed through a custom-built, CdMnTe-based micro-optical isolator. The isolator has a total length of 10 mm and an outer diameter of 5 mm; it features a transmission of about 40% and an isolation of 27 dB. The light behind the isolator is coupled into a polarization-maintaining (PM) single-mode fiber using an aspherical lens. The optical output power of the fiber is 1.7 mW.

10100-47, Session 9

Growth of GaAs/AlAs distributed Bragg reflector on a concave GaAs substrate

Kouichi Akahane, Tetsuya Ido, Naokatsu Yamamoto, National Institute of Information and Communications Technology (Japan); Kazuto Mochizuki, Yusuke Furukawa, The Univ. of Electro-Communications (Japan)

High reflection dielectric distributed Bragg reflector (DBR) can be used with high Q optical cavity to narrow down the spectrum optical source, for experimental quantum electro-dynamics, etc. To construct a free space optical cavity for a local oscillator of the state-of-the-art optical frequency standards, concave mirrors are used as one of the end mirrors of the cavity. Usually, the high reflection DBR is fabricated by depositing dielectric materials on a glass substrate. However, the ultimate stability of the optical cavity is limited by the thermal noise of dielectric DBR. To overcome this problem, a crystalline DBR was proposed to stabilize the optical cavity, which can reduce thermal noise. In this study, we fabricated crystalline DBR by GaAs/AlAs compound semiconductor on a concave GaAs substrate. Although a traditional semiconductor substrate has atomically flat surface, we fabricated a concave surface with a curvature radius of 1000 mm on the GaAs substrate by optical quality polishing. Then, we carried out wet etching and introduced it in vacuum chamber for molecular beam epitaxy (MBE). In the MBE growth chamber, we carried out thermal cleaning with As4 at a substrate temperature of 600°C. Next, the GaAs/AlAs DBR structure was grown at 580°C. The evaluation of surface roughness was conducted by atomic force microscopy, which showed a roughness of 0.165 nm in 1 ? 1 um measurement such that a very smooth surface can be obtained.

10100-48, Session 9

CMOS SiPM with integrated amplifier

Alexander Schwinger, Werner Brockherde, Fraunhofer-Institut für Mikroelektronische Schaltungen und Systeme (Germany); Bedrich J. Hosticka, Holger Vogt, Fraunhofer Institute for Microelectronic Circuits and Systems (IMS) (Germany) and University of Duisburg-Essen (Germany)

The integration of SiPM and frontend electronics in a suitable optoelectronic CMOS process is a promising approach to increase the versatility of SPAD-based single-photon detectors. By integrating readout amplifiers, the device output capacitance can be reduced to minimize the waveform tail, which is especially important for large area detectors (> 10x10mm?). Possible architectures include a single readout amplifier for the whole detector, which reduces the output capacitance by ~1 pF at minimal reduction in detector active area. On the other hand, including a readout amplifier in every SiPM cell would greatly improve the total output capacitance by minimizing the influence of metal routing parasitic capacitance, but requiring a prohibitive amount of detector area. As tradeoff, the proposed detector features one readout amplifier for each column of the detector matrix to allow for a moderate reduction in output capacitance while allowing the electronics to be placed in the periphery of the active detector area. The presented detector with a size of 1.7 x 1.0 mm? features 400 cells with a 50μm pitch, where the signal of each column of 20 SiPM cells is summed in a readout channel. The 20 readout channels are subsequently summed into one output channel, to allow the device to be used as a drop-in replacement for commonly used analog SiPMs.

10100-49, Session 9

Design and characterization of 1.1 micron pixel image sensor with high-NIR quantum efficiency

Zach Beiley, Andras Pattantyus-Abraham, Bo Chen, Andrey Kuznetsov, Erin Hanelt, Naveen Kolli, Edward H. Sargent, Jae Park, InVisage Technologies, Inc. (United States)

Internet of Things devices and unmanned vehicles benefit from near-infrared (NIR) machine vision. Even more widespread implementation of these technologies will require NIR imaging exhibiting increased sensitivity, higher resolution, lower power consumption, and the ability to overcome solar irradiance outdoors. The unprecedented sensitivity of QuantumFilm enables a comprehensive solution to these NIR camera sensor challenges.

At the 940 nm wavelength, solar background irradiance is relatively low and device-mounted monochromatic LED emission can be used to illuminate and assess the shape, distance, and optical properties of objects. We report

here NIR imaging that outperforms existing CMOS sensors by achieving record quantum efficiency at 940 nm for a 1.1 um pixel.

The rationally engineered material properties of QuantumFilm allow tuning of the spectral response to the desired wavelength to achieve quantum efficiency that exceeds 40%. In addition, the combination of high QE with QuantumFilm's distinctive film-based electronic global shutter mechanism allows for extremely low illumination power, and therefore time-averaged system power, during actively-illuminated imaging.

This presentation describes the design and resultant beneficial properties of QuantumFilm and pixels made using this new material; the optical stack of the QuantumFilm image sensor; and QuantumFilm device performance with that of conventional silicon sensors. It also outlines a roadmap for further advances in performance.

10100-50, Session 10

Sensors based on silicon photonic crystal mirrors with engineered phase delay

(Invited Paper)

Olav Solgaard, Stanford Univ. (United States)

Photonic Crystal (PC) mirrors derive their optical properties from interferences between propagating modes and guided resonances of the PC. The guided resonances store energy and give the PC mirrors highly dispersive phase responses [1], which can be engineered for practical advantage in a number of sensor applications. In addition to flexible phase response, Silicon PC mirrors may also be made as monolithic crystalline structures resulting in devices with excellent mechanical strength and chemical robustness that make them ideal for sensor applications where miniaturization, ability to operate in challenging environments, and long term stability are important.

In this talk we outline fundamental characteristics, scaling properties, and design of Photonic Crystal sensors. We cover fabrication of monolithic Si PCs using well-established Si foundry technologies, and we report on experimental verification of their dispersive phase responses. We show that the dispersive phase response can be engineered to control the "penetration depth" of the mirrors over a wide range of values. This can be used to create "negative thickness" Fabry-Perot resonators, and anomalous Goos-Hanchen shifts.

Finally, we conclude the talk with examples of practical Silicon Photonic Crystal Sensors, in which engineering of the phase response improves sensor characteristics. These devices include sensors for pressure, temperature, chemical composition and Atomic Force Microscopy.

1. A. Gellineau, Y.-P. Wong, O. Solgaard, "Engineering-reflected phase in Fabry–Perot sensors with resonant mirrors", Optics Letters, vol. 38, no. 23, pp. 4992–4995, December 1, 2013.

10100-51, Session 10

Tailoring the optical properties of one-dimensional (1D) photonic structures

(Invited Paper)

Alessandro Chiasera, Istituto di Fotonica e Nanotecnologie (Italy); Luigino Criante, Istituto Italiano di Tecnologia (Italy); Stefano Varas, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Giuseppe Della Valle, Politecnico di Milano (Italy); Roberta Ramponi, CNR-Istituto di Fotonica e Nanotecnologie (Italy) and Politecnico di Milano (Italy); Ilka Kriegel, Istituto Italiano di Tecnologia (Italy); Michele Bellingeri, Univ. degli Studi di Parma (Italy); Davide Cassi, Univ. di Parma (Italy); Giancarlo C Righini, MipLAB. IFAC - CNR (Italy) and Centro di Studi e Ricerche "Enrico Fermi" (Italy); Francesco Scotognella, Politecnico di Milano (Italy)

We present here the possibility to tailor the optical properties of 1D photonic structures by using more than two materials [1] and by clustering the high refractive index (hRI) layer in the structures [2]. The light transmission spectra of studied 1D photonic structures have been simulated by employing the transfer matrix method. In particular, we show that: i) with a photonic crystal made of i different materials, the corresponding photonic band gap splits in i-1 bands; ii) when the size of the hRI layer clusters, randomly distributed within the low refractive index layers, follows a power law distribution, the total light transmission follows a sigmoidal function. We stress that the second structure, characterized by hRI layer clusters, need a relatively high number of layers (2880 layers in the reported study [2]). Furthermore, we discuss the fabrication aspects to realize the above mentioned photonic structures [3], in terms of a judicious choice of the materials to employ in the photonic structures and in terms of the most suitable deposition technique to achieve 1D photonic structures with a high number of layers.

The proposed photonic structures could be interesting for multi-feature optical filters and for light trapping in photovoltaic devices.

References:

[1] Kriegel et al., http://dx.doi.org/10.1016/j.optcom.2014.10.045

[2] Bellingeri et al., DOI: 10.1109/JLT.2015.2460259

[3] Chiasera et al., doi:10.1166/sam.2015.2249

10100-52, Session 10

Different designs and glass compositions of chalcogenide microstructured optical fibers for different applications

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Chalcogenide glasses are known for their large transparency in the mid-infrared (Mid-IR) and their high nonlinear optical properties. Indeed, chalcogenide glasses can present a high non-linear coefficient (n2), 100 to 1000 times larger than for silica glass, depending on the composition. An original way to obtain fibers is to design microstructured optical fibers (MOFs). These fibers present unique optical properties thanks to the high degree of freedom in the design of their geometrical structure. Various chalcogenide MOFs operating in the mid-IR range have been elaborated in order to associate the high nonlinear properties of these glasses and the original MOF properties. Different glass compositions and different designs have been achieved depending on the intended application. Indeed, chalcogenide MOFs might lead to new devices with unique optical properties in the Mid-IR domain like multimode or endlessly single mode transmission of light, small or large mode area fibers, non-linear properties for wavelength conversion or generation of supercontinuum sources. In the 1-12 µm window, single mode fibers, polarization maintaining fibers and exposed core fibers have been realized for Gaussian beams propagation and sensors applications. In this context, different applications such as Brillouin laser, all optical demultiplexing, mid-IR supercontinuum generation, quantum cascade laser pigtailing and mid-IR spectroscopy will be exposed.

10100-53, Session 10

Enhanced electro-optical two-dimensional photonic crystal slab for E-field detection

Venancio Calero, Wentao Qiu, Miguel Ángel Suárez, Roland Salut, Abdoulaye Ndao, Alexis Caspar, Fadi Issam Baida, Nadège Courjal, Maria-Pilar Bernal, FEMTO-ST (France)

In electric field sensing the non-intrusive feature is very convenient in order to avoid disturbances on the electric field to be measured. For this reason, all-dielectric and small cross-area devices are suitable for such application. In this work, we present an optical e-field sensor based on a 2-dimensional Fano photonic crystal slab (Fano PCS) designed on an air coated thin film of lithium niobate (TFLN) which exploits the electro-optical tunability enhancement provided by the Fano resonance resulting from an optimized PCS geometry relying on a Finite Difference Time Domain (FDTD) assisted design procedure. The illumination direction is perpendicular, simplifying the light coupling and enhancing the light-matter interaction due to the reduced group velocity calculated by the PWE method at the gamma direction, allowing extremely high sensitivity of the order of uV/m. This configuration will lead to a high sensitive, compact (several micrometers of footprint) and non-intrusive e-field sensor. Finally, we will demonstrate the theoretical and experimental electric field sensing performances.

10100-54, Session 10

Mid- and far-infrared optical characterization of monoclinic HfO2 nanoparticles and evidence of localized surface phonon polaritons

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Monoclinic hafnia (m-HfO2) nanoparticles are prepared via a sol-gel method and characterized via angle-, wavelength-, and polarization-dependent transmission and reflection spectroscopy from the mid- to far-infrared using a Fourier transform infrared spectrometer (FTIR). Spectra of the nanoparticles with sizes ranging from 10 – 60 nm are dominated by optical phonon absorption in the Reststrahlen band of the m-HfO2 crystal (~250 – 800 cm-1). The absorption features in the measured transmission and reflection agree well with measurements of m-HfO2 thin films in literature; however, the spectra do differ because light can couple to additional optical phonons in the nanoparticles due to the distribution of crystal orientations relative to the incident light. The optical phonon energies are estimated using a transfer matrix method with a permittivity that is the sum of many Lorentizian lineshapes (one for each optical phonon). The recovered phonon energies and oscillator strengths agree well with infrared measurements on thin films and values predicted by density functional perturbation theory (DFPT). An anomaly is observed in the transverse magnetic transmission and reflection data around 585 cm-1 that is not accounted for by an optical phonon. In this spectral region, the permittivity is estimated as -2 using the recovered dielectric function. Numerical models predict that a localized surface phonon polariton should exist in this region on the HfO2 nanoparticles. This work could lead to mid- and far-infrared materials and devices with engineered optical properties using HfO2 nanoparticles.

10100-55, Session 11

Optomechanical effects in single-mode and multi-core fibers *(Invited Paper)*

Yair Yair Antman, Hagai Diamandi, Yosef London, Alex Clain, Avinoam Zadok, Bar-Ilan Univ. (Israel)

No Abstract Available

10100-56, Session 11

Coherent supercontinuum in a silicate glass composite fiber with all-normal dispersion

Xia Li, Shanghai Institute of Optics and Fine Mechanics (China); Jiang Li, Shanghai Institute of Ceramics (China); Tonglei Cheng, Toyota Technological Institute (Japan); Danping Chen, Shupei Zheng, Wanjun Bi, Shanghai Institute of Optics and Fine Mechanics (China); Weiqing Gao, Hefei Univ. of Technology (China); Yasutake Ohishi, Toyota Technological Institute (Japan)

A highly coherent broadband light source is necessary for several applications, such as biological imaging, molecular detection techniques, pulse compression, and frequency metrology. Typically, a flat all-normal dispersion for coherent supercontinuum generation (SCG) is achieved in photonic crystal fibers (PCFs) with small air-hole size and mode field area. But the fiber always pocesses high confinement loss and complex fabricating procedure. Post processing of air-hole PCFs is also challenging.

Therefore, we fabricated all-solid composite fibers of all-normal dispersion for coherent SCG. The fiber was drawn directly from a preform with a yttrium aluminum garnet (YAG) rod inside a silica tube. The eventual fiber was formed with a silica cladding and a yttria-alumino-silicate glass core. The fiber was tested with scanning electron microscopy (SEM), transmission electron microscope (TEM) and electronic probe micro-analyzer (EPMA). Fiber loss and splicing loss were also measured. Fibers with different core size were pumped with femtosecond laser sources at different wavelengths. With a large core size in fiber A, soliton related phenomena extended the SC enormously at anomalous dispersion region. With a smaller core size, fiber B achieved a flat normal dispersion. The simulated and measured SC spectra affirmed this statement. With 440 mW pumping, a spectrum ranging from ~1233 to 1572 nm was measured. The simulation revealed that the SC could reach more than one octave from ~920 to 1950 nm in fiber B. The generated spectra in fiber B were flat and have good coherence. The SC pumped at 1.75 ?m and 1.06 ?m has also been shown.

10100-57, Session 11

Fatigue behavior of polyimide coated optical fibers at elevated temperatures

Lei Huang, OFS (United States)

The mechanical strength and reliability of optical fiber at high temperature have become important subjects as optical fibers are increasingly used for harsher environments. The majority of the knowledge of optical fiber's mechanical properties and lifetime predictions exist around traditional uses in optical telecommunication, and thus need to be validated at high temperatures. Published data reveal that the fatigue of optical fiber is dependent on temperature and thus may accelerate at high temperatures. In this paper, we report initial results of fatigue behavior of polyimide coated optical fiber at 300 and 350ºC. The results are compared with room temperature data, and data available in the literature.

10100-58, Session 11

Elastic stability of a dual-coated fiber-optic connector

Ephraim Suhir, ERS Co. (United States); Sung Yi, Portland State Univ. (United States)

A simple and physically meaningful predictive analytical (mathematical) model is developed for the evaluation of the critical force for a dual-coated fiber-optic connector. The obtained results can be used in the analysis and physical design of connectors of the type in question. They can also be used in tensors and actuators employing fiber optics technologies. These results can be used also beyond the optical engineering field, when there is a need to evaluate the elastic stability of a cantilever beam partially supported by an elastic foundation.

The coatings in the connector in question are applied (cured) at an elevated temperature, and the structure is subsequently cooled down to a low

(room, operation, testing) temperature. The thermal contraction mismatch between the high-expansion secondary coating and the low-expansion glass fiber results in a thermally induced compressive force in the fiber. The major compression comes, however, from the external (mechanical) compression, when the stripped off end of the connector experiences, in actual operation conditions, significant compressive force. This force has to be high enough to produce an adequate pressure on the connector tip, but should not be higher than necessary, so that elevated buckling and post-buckling deformations, if any, are avoided. The ability to determine the effective critical force for a typical optical fiber connector module is of obvious practical importance. The objective of the analysis is to develop a simple and physically meaningful predictive model for the evaluation of this force. The obtained results can be used also in the analyses of tensors and actuators employing fiber optics technologies.

10100-59, Session 11

Side-polished fiber medicated by cholesteric liquid crystal and its characteristics of organic vapor sensing

Jieyuan Tang, Zhe Chen, Jianhui Yu, Huihui Lu, YunHan Luo, Heyuan Guang, Jun Zhang, Jinan Univ. (China)

In this work, we proposes a novel fiber device by coating Cholesteric liquid crystal (CLC) film on the polished surface of a single mode side-polished fiber and demonstrates its sensing characteristics of organic vapor. A wheel polished technique was employed to fabricate a single mode side-polished fiber (SM-SPF) with ~0?m residual cladding thickness, which promotes the effective interaction between the optical field in SM-SPF and the surrounding material. The CLC, a mixture of three cholesterol compounds, utilized as sensitive materials, was deposited onto the polished surface of a SM-SPF to form a CLC layer of several micrometers thickness. Their characteristics of organic vapor sensing are investigated experimentally. The results show that transmission resonance spectrum of the fiber device blue-shifts when being exposed in organic vapor. The sensitivity is related to the resonance wavelength, and the longer resonance wavelength gives higher sensitivity. When the resonance wavelength is about 680nm, the fiber device gives highest sensitivity: that is 7.08nm/mmol for the tetrahydrofuran vapor . But the linear correlation coefficient is only 93.6%, and the resonance spectrum gradually deteriorated when the concentration of the vapor reached 4.937nm/mmol. For methanol vapor, the sensitivity is only 0.515nm/mmol, and the linear correlation coefficient is just 88.5%. So the fiber device is no suitable for the methanol vapor. For acetone vapor, the sensitivity is 3.46nm/mmol when the concentration increases from 0mmol/l to 12mmol/l and the corresponding linearity is 0.9941. This fiber device is suitable to be used to monitor the acetone vapor in a small airtight space.

10100-19, Session PWed

Optimization of the parameters of space-based mirrors

Nadezhda D. Tolstoba, Daria Butova, Maria Orekhova, ITMO Univ. (Russian Federation); Alexander Fleysher, The Vavilov State Optical Institute (Russian Federation)

With the aim of creating a lightweight large-sized primary mirror of space-based telescope, and saving of its strength when there are starting loads and outlined a plan of action:

1. Consideration of the deformation occurring in the mirror with classic relief structures for a given diameter and a ratio of thickness / diameter: edge-ring, cellular, etc., and to find the optimal ratio parameters of mirror: diameter, thickness of the mirror, the thickness of the stiffener structure.

2. Comparison of the deformations of the optical surface of the mirror in the shape of a bowl with its deformation in the classical relief.

3. Search of dependencies deformation surface of the very thin mirror on the thickness of the mirror and mirror diameter.

4. Calculation of the shape of the mirror surface under the influence of the gravitational component.

5. Identify the ratio of diameter to thickness of the mirror to achieve acceptable deformation of the optical surface

6. Creating a cut of the mirror with the following: the calculated ratio of thickness to diameter for a given diameter, the necessity for discharging structures, construction of the telescope farm to which the mirror will have to be consolidated.

10100-40, Session PWed

Highly nonlinear chalcogenide hybrid microstructured optical fibers with buffer layer and their potential performance of supercontinuum generation

Hoang Tuan Tong, Kenshiro Nagasaka, Trung Hoa Nguyen Phuoc, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

We reported here the potential performance of supercontinuum (SC) generation by using highly nonlinear chalcogenide hybrid microstructured optical fibers (HMOFs) whose chromatic dispersion profiles were near-zero and flattened in the range from 4.5 up to 11.0 μm. A chalcogenide HMOF was first designed with a high-index core surrounded by a ring of six air holes in the cladding. The AsSe2 glass was used as the core and the Δn between AsSe2 and cladding materials was supposed to be 0.3. The calculated chromatic dispersion profile had a broad normal dispersion regime up to 9 ?m which was disadvantageous to obtain broadband SC generation. In order to tailor the chromatic dispersion profile, a buffer layer which enclosed the core was added. The Δn between the core and buffer materials was 0.02. By using this new structure, an anomalous dispersion regime was obtained from 4.5 ?m. The chromatic dispersion could be close to zero and flattened from 4.5 up to 11.0 ?m by changing the radius of the air holes and buffer layer. In addition, the chromatic dispersion fluctuation caused by the fiber structure variation was greatly suppressed. When a 1-cm-long section of this fiber is pumped at 5.0 ?m by a pulsed laser whose peak power is 1kW, the calculated effective mode area is 17.43 ?m2, the nonlinear coefficient is 1.66 W-1m-1 and an SC whose spectrum spans from 2.5 to 16 ?m can be generated as shown in our numerical calculation.

10100-60, Session PWed

Stimulated Raman scattering in AsSe2-As2S5 microstructured optical fiber

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We demonstrate the effects of stimulated Raman scattering (SRS) in the all-solid-core chalcogenide microstructured optical fibers (MOFs) with AsSe2 core and As2S5 cladding, which are fabricated by the rod-in-tube drawing technique. The core diameters of the MOFs are ~6.3 (Fiber I), 3.0 (Fiber II), 2.6 (Fiber III) and 2.2 (Fiber IV) ?m, respectively. The chromatic dispersion of the fundamental mode in Fibers I-IV is simulated by the full-vectorial mode solver technique. The first-order Stokes wave is investigated in the fibers with different core diameters pumped by the picosecond pulses at 1958 nm. In Fiber I, no obvious Raman peak is observed with the pump power increasing, because the effective nonlinearity is not high. In Fiber II, a Raman Stokes peak at ~2065 nm begins to emerge at the pump power of 110 mW. The conversion efficiency is as weak as -36.6 dB at 150 mW pumping. In Fiber III, the first-order Raman peak at ~2060 nm begins to emerge at

40 mW pumping. The conversion efficiency is -15.0 dB, which is 21.6 dB higher than that in Fiber II. In Fiber IV, the Stokes peak at 2070 nm begins to appear at 56 mW pumping. The maximum conversion efficiency of the first-order Stokes wave is obtained in the MOF with the core diameter of 2.6 ?m. The evolution of the first-order Stokes wave with pump power and fiber length is investigated. This is the first demonstration of Raman effects in the AsSe2-As2S5 MOF, to the best of our knowledge.

10100-61, Session PWed

Nanophotonic chemical sensor using rare-earth upconversion phosphors

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The objective of the paper was to demonstrate feasibility of a chemical (ammonia) sensor using dye-doped polymer nanocomposite with upconversion phosphor nano-particles. The micro-crystalline powder of upconversion rare-earth phosphor NaYF4:Yb3+, Er3+ was synthesized using a simple wet process followed up by baking in open air. The powder was reduced into nano-colloid with 100-nm nano-particles using the ball milling process. The nano-colloid was added to the solution of polymer poly(methyl methacrylate) known as PMMA. Additionally, a pH indicator dye (Phenol Red or Bromothymol Blue) was dissolved in polymer solution. The dye-doped polymer nanocomposite films were deposited on substrates using the dipping process followed by baking in order to evaporate the solvent. in the form of dopants and micro-powder additives in order to bring up the chemical sensing functionality. The deposited nano-photonic sensor film retained bright green upconversion fluorescence with a spectral peak at 540 nm attributed to the nano-photonic rare-earth phosphor pumped with a 980 nm infrared diode laser. The spectrum of green emission matched the absorption band of the indicator dye exposed to ammonia. When the film was exposed to ammonia, it demonstrated an optical response in the form of the drop of intensity of green radiation measured with a silicon photodiode power meter. The sensitivity of the developed chemical sensor was close to 0.4% ammonia in air, and the response time was close to 5 minutes

10100-62, Session PWed

PMMA microlens array fabricated by indentation process

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This work reports the fabrication of a PMMA-based spherical microlens array (MLA), targeting application of Shack-Hartmann wavefront sensor for lens characterization. The fabrication method employs a computer-controlled mechanical indentation for the fabrication of an insert mold, and subsequent replication by thermo injection on PMMA. The array present 10 by 10 elements, with f-number f/# = f/10 (1000 ?m diameter, 10 mm focal length). The mold insert of the MLA consists of a hardened steel substrate (Hardness Vickers 815 kgf/mm2) indented by a ball nose actuator. The indentation conditions were: loading of 1000 gf, load pressure of kgf/mm2, indentation cycle of 15s, and a penetration speed of 60 um/s. After replication and de-molding, the PMMA surface containing the negative of the phase profile of the lens array was evaluated by optical profilometry technique, in terms of the surface quality as well as the replication fidelity. The RMS surface roughness level of approximately (? / 20) was found, considering operation in the visible range of spectrum. A replication fidelity between 98.5 % and 99.5 % was obtained, indicating a relatively good fidelity.

Optical characterization was based on the evaluation of the FWHM values associated to the intensity profiles of each of the 100 light spots, obtained in the back focal plane of the MLA. The FWHM deviation was less than 9%. This value is adequate, considering applications of wavefront sensors.

10100-63, Session PWed

Relative humidity sensor using a periodically micro-tapered long-period fiber grating depending on the waist diameter of the microfiber

Jong Cheol Shin, Ju Il Hwang, Seungmin Lee, Young-Guen Han, Hanyang Univ. (Korea, Republic of)

The humidity sensors have been widely implemented in a variety of applications, such as air conditioning, food manufacture and civil engineering. Many relative humidity (RH) sensing techniques, such as wet and dry bulb psychrometer, chilled mirror hygrometer, and electronic hygrometer have been proposed. However, they have drawbacks of corrosion, long response time, and electromagnetic interference. The fiber-optic humidity sensors have many advantages, such as immunity to electromagnetic interference, good stability, and greater resistance to corrosion. Many techniques for fiber-optic humidity sensors, such as long-period fiber gratings (LPGs), fiber Bragg gratings, and plastic optical fibers incorporating hydrogel, polyvinyl sulfonic acid (PVS), and hydrophilic gel have been reported. The previous humidity sensors, however, have many disadvantages, such as high insertion loss, low accuracy and low sensitivity to humidity.

In this paper, a simple scheme for the RH sensor based on a periodically micro-tapered LPG with the low index polymer (CYTOP, nCYTOP=1.34) and the PVA (npva=1.50) overlays is proposed and experimentally demonstrated. Absorbing humidity of the PVA overlay in the proposed micro-tapered LPG changes the effective refractive index of the cladding modes depending on the diameter of the micro-tapered fiber. Since the cladding modes of the micro-tapered LPG are sensitive to ambient index change, the resonant wavelengths depending on the cladding mode order will be varied. In addition, the low index polymer can effectively suppress the sensing uncertainty of the proposed RH sensing probe.

10100-64, Session PWed

Strain sensitive enhancement of fiber Bragg grating sensing probe using weak value amplification

Kwang-Wook Yoo, Ik Su Jo, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

Fiber gratings classified by fiber Bragg gratings (FBGs) and long-period fiber gratings (LPFGs) have been attracting much attention in optical sensors because of their many advantages, such as wavelength-selective nature, easy adaptability, low loss, etc. External perturbations essentially change the center wavelength of fiber gratings. The weak value amplification (WVA) technique was proposed to improve the sensitivity of the fiber grating sensor to external perturbation. Recently, the polarization-based WVA was investigated to enhance the temperature sensitivity of the FBG sensor. The previous method, however, has many drawbacks, such as complicated structure, instability of experimental setup, and experimental inconvenience due to polarization. In this paper, we propose a new method of the WVA based on the optical attenuation to improve the performance of the FBG sensor, which has a simple structure compared to the polarization-based WVA. The strain sensitivity of the FBG sensor using the proposed attenuation-based WVA is successfully enhanced.

10100-65, Session PWed

Spectroscopic and photothermal characterization Er-doped phosphate glass

Djalmir N. Messias, Vanessa M. Martins, Acácio A. Andrade, Viviane Pilla, Noelio O. Dantas, Univ. Federal de Uberlândia (Brazil)

The design of optical devices demands a deeper control over all the physical process capable to change its behaviour. Among these processes, that related to the nonradiative transitions are highlighted because they can increase the heat deposited on these devices, and consequently diminish the luminescence quantum efficiency. In special, Er-doped optical devices has proved to be a versatile material system with a wide range of applications, including broadband optical sources, wide-band optical amplifiers, and tunable lasers. In this work optical spectroscopic characterization was performed in a Er-doped phosphate glass matrix. The glass matrix, termed as PAN (P2O5-Al2O3-Na2CO3), was doped with increasing Er3+ concentration. Due to its high phonon energy, only the 1550 nm emission band was observed. Therefore, we have applied the normalized lifetime thermal lens technique in order to determine the luminescence quantum efficiency of this emission. These results were compared with that obtained with the standard Judd-Ofelt calculations. Besides absorption spectra, emission spectra as also obtained. Therefore, the gain coefficient spectra could be evaluated for different population inversions. Finally, figures of merit for the optical amplifiers were estimated and compared with others Er-doped materials. Through these spectroscopic characterization we determined that the Er:PAN system is a good candidate for application in optical devices.

10100-66, Session PWed

Determination of nonlinear optical properties by time resolved Z-scan in Nd-doped phosphate glass

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In intense pumped system, great ground state depletion can be achieved in ion doped materials. This can induce several deleterious effects on different optical devices. This population redistribution changes the optical susceptibility and therefore the nonlinear index of refraction, n2. In Nd-doped solids the nonlinearity comes mainly from the high-energy transitions, usually in the ultraviolet (UV), that stems from the 4f ? 5d and charge transfer band transitions, respectively. Although these transitions are in the UV they have oscillator strength ~ 104 larger than the transitions in the visible. So, the susceptibility, and therefore the nonlinear refractive index, has its major contributions from these UV transitions. In addition, in ion-doped solids, it is well known that the polarizability difference between excited and ground states, ??, is proportional to the nonlinear refractive index. Therefore, following the above arguments, one can assume that the main contribution to ?? comes from these UV transitions. In this work, we performed time-resolved measurements using the time resolved z-scan technique to characterize the nonlinear optical properties of Nd-doped phosphate glasses, as n2 and ??. The glass matrices, termed as PAN (P2O5-Al2O3-Na2CO3) and PANK (P2O5-Al2O3-Na2O-K2O), were doped with increasing Nd3+ concentration. Using cw laser excitation, it was possible to average the nonlinear optical properties over the different dopant concentrations.

10100-67, Session PWed

Study of the thermal-optics parameters of Nd3+-doped phosphate glass as a function of temperature

Acácio A. Andrade, José Carlos Filho, Viviane Pilla, Djalmir N. Messias, Univ. Federal de Uberlândia (Brazil); Sidney A. Lourenço, Univ. Tecnológica Federal do Paraná (Brazil); Anielle Christine Almeida Silva, Univ. Federal de Uberlândia (Brazil); Noelio de Oliveira Dantas, Univ. Tecnológica Federal do Paraná (Brazil)

The spectroscopic properties of rare earth ions in many different hosts have been investigated, including surveys of Nd3+ in silicate, phosphate, fluorophosphates and fluoride glasses. The neodymium ions have important characteristics that distinguish them from the others optically active ions, mainly because the wavelengths of emission and absorption transitions are insensitive to the host material. On the other hand, phosphate glasses have been studied for showing great optics and thermal properties. Also, neodymium ions present high quantum efficiency in these matrices. The solubility of rare earth ions in these glasses and its infrared transparency make them a good material for laser application. However, it is known that during laser operation, the active material undergoes a temperature increase, which can cause changes in its properties, interfering in the laser performance, mainly in luminescent and mechanical properties.

Some of the thermal-optical properties of materials are influenced by temperature change, such as thermal diffusivity, specific heat and luminescence quantum efficiency. Thus, the characterization of these properties are very important to be evaluated for materials that have the potential to become active laser medium.

The aim of this work is therefore to characterize a phosphate glass matrix called PANK doped with different Nd3+ ion concentrations using thermal lens technique as a function of temperature from 80 to 480 K. Complementary measurements to obtain the optical absorption coefficient, luminescence spectra and lifetime, also as a function of temperature, were also carried out.

10100-70, Session PWed

White-light emission characteristics of rare-earth ion-doped Sodium borate glass

Rami R. Bommareddi, Alabama A&M Univ. (United States)

Sodium borate glass embedded with rare-earth ions was made by the melt quenching technique. Under a blue diode excitation it revealed strong emission in the visible wavelength region at several wavelengths. The color of the emission spectrum is close to that of warm white light. The CIE color co-ordinates and color temperature are estimated after analyzing the spectra. Glass composition is varied so that the emission color appears more like that of an incandescent light bulb.

10100-71, Session PWed

Backside-incidence critically-coupled Ge on SOI photodetector

Yu-Hsuan Liu, National Tsing-Hua Univ. (Taiwan) and Artilux Inc. (Taiwan)

For present-day optical communication systems, the commonly used normal-incidence photodetectors suffer from the tradeoff between responsivity and bandwidth. Such a tradeoff is especially adverse for long wavelength communication systems operating at higher data rates. For example, the maximum responsivity for a commercially available 25 Gbps

photodetector operating at 1310 nm wavelength is limited to less than 0.8 A/W. In this work, we design and demonstrate a high-speed, backside-incidence critically-coupled Ge on SOI (Silicon-on-Insulator) photodetector operating at 1310 nm while maintaining a high quantum efficiency. With appropriate optimizations, a responsivity as high as 0.95 A/W at 25 Gbps can be obtained. The device is fabricated with low temperature RPCVD epitaxy, i-line lithography, nickel silicide contact, and Al interconnect system, which are fully compatible with the state-of-art CMOS process technology. With optimized epitaxial scheme and surface passivation procedure, a low dark current of 17 mA/cm2 is obtained from a thin 0.66 μm thick Ge device at -1 V bias at room temperature. The measured photocurrent enhancement near 1310 nm wavelength closely matches the FDTD simulation result, and a complete device characterization is currently in progress. Our backside-incidence critically-coupled Ge on SOI photodetector may serve as a high-performance and low-cost solution for next generation high-speed optical receivers, and its benefit of decoupling bandwidth and quantum efficiency is especially prominent at higher data rates such as 40 Gbps and beyond.

10100-72, Session PWed

Luminescent properties and phase transition in Er3+-Yb3-co-doped NaYF4/SiO2 core-shell nanoparticles

Xiaojie Xue, Tonglei Cheng, Weiqing Gao, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

We successfully synthesized Er3+-Yb3+ doped cubic phase NaYF4 nanocrystals by a facile solvethermal method. The average size of the as-prepared nanocrystals was about 12 nm based on the observation of scanning electron microscope and transmission electron microscope. NaYF4/Silica nanoparticles were prepared. The thickness of shell layer was about 7 nm. The as-prepared samples were annealed at different temperature. The cubic phase NaYF4 did not transit to hexagonal phase, but to amorphous phase as the annealing temperature increased to 700 C. When temperature further increased to 1100 C, the amorphous NaYF4 reacted with SiO2 shell and formed a new phase, NaYSiO4. Under the excitation by a 976 nm laser, the Er3+-Yb3+ doped NaYF4, NaYF4/SiO2, and NaYSiO4 nanoparticles showed intense visible upconversion emissions and near-infrared emissions. Since the host materials changed from fluoride crystals to amorphous fluoride, then to silicate crystals, the spectral profiles were different. Fluorescent lifetimes obtained from decay curves were applied to analyze the multi-phonon relaxation processes in different hosts. Quantum efficiency of the as-prepared samples was measured under 976 nm laser pumping with various power. The quantum efficiency enhanced with the phase transition processes of host materials. The mechanism of phase transition in the core/shell nanoparticles was proposed. The Er3+-doped upconversion phosphors will be useful for light converting in solar cell applications in the future.

10100-73, Session PWed

Experimental Observation of Stimulated Raman Scattering in a Fluoride Fiber

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Fourth-order cascaded Raman shift in a birefringence ZrF4?BaF2?LaF3?AlF3?NaF (ZBLAN) fluoride fiber was investigated in this paper. To the best of our knowledge, this is the first demonstration of fourth-order cascaded Raman shift in fluoride fibers. The pump source was a picosecond laser with the center wavelength of 1064 nm. At the average pump power of ?7W, fourth-order cascaded Raman shift was observed if the pump pulse was polarized to the slow axis, and only third-order cascaded Raman shift was obtained if the pump pulse was polarized to the fast axis. Furthermore, the generalized nonlinear Schrödinger equation (GNLSE) was used to simulate the cascaded Raman shift generation process, and the results were in good agreement with the experiments.

10100-74, Session PWed

Mid-infrared rogue wave generation in chalcogenide fibers

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The emergence of high-amplitude events that occur with low probability is an intrinsic property of many physical systems which has a dramatic impact on the performance of the system. Optical rogue wave was first used to describe the instabilities in optics in long-tailed histograms in measurements of intensity fluctuations at long wavelengths in fiber supercontinuum spectra. The term "rogue wave" comes from the analogous physics of nonlinear wave propagation in optics and hydrodynamics. The generalized nonlinear Schrödinger equation including the noise can be used to describe the rogue wave generation in fibers. The noise has a great effect on the rogue wave generation because the rogue waves are originated from the modulation instability which can exponentially amplify the noise. For supercontinuum generation based on chalcogenide fibers, the damage threshold is much lower than the silica glass. Therefore, the generation of rogue waves would greatly increase the chance of damage in supercontinuum generations using chalcogenide fibers. In this paper, the rogue wave generation in a step-index chalcogenide fiber is numerically investigated by solving the generalized nonlinear Schrödinger equation. Three noise sources have been used to model the effect of shot noise of the pump laser. The quantum noise is modeled by using one-photon-per-mode-noise and phase diffusion-noise. The technical noise is modeled by using amplitude noise. The ratio of amplitude noise is changed to describe the coherence property of pump laser. The results show that the rogue wave power statistics are greatly affected by the pump source noise property.

10100-75, Session PWed

Mid-infrared supercontinuum generation in chalcogenide multi-step index fibers with normal chromatic dispersion

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We experimentally demonstrated mid-infrared supercontinuum (SC) generation in chalcogenide multi-step index fibers (MSIF) pumped by a femtosecond laser. The fabricated chalcogenide MSIF was composed of a high refractive index core (C1) in the center, which was enclosed by a lower refractive index core layer (C2) and an outer cladding. This fiber structure is advantageous to tailor the chromatic dispersion with higher freedom and to keep the effective mode area small at long wavelengths. The high refractive index core, low refractive index core and the outer cladding materials were As2Se3, AsSe2 and As2S5, respectively. When the diameter of C1 and C2 were 7.8 and 30 ?m, respectively, the zero-dispersion wavelength (ZDW) of the fiber was at 12.5 ?m. The chromatic dispersion profile was near-zero and flattened within the range of +-20 ps/km/nm in the wavelength range from 4 to 17 ?m and a broad normal dispersion region was obtained in the wavelength range shorter than the ZDW. In practice, a 2.8-cm-long fiber was pumped at 10 ?m by using a femtosecond laser whose pulse width was ~200 fs. The SC generation spanning from 2 to 14 ?m was obtained. Most of its spectrum was in the normal dispersion region of the fiber. These results are promising for the highly coherent mid-infrared SC generation.

10100-76, Session PWed

Organic plasmonic Mach-Zehnder modulator with direct coupling to silicon waveguides

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A bottle neck in the quest of building faster computers is the low bandwidth problem of the electrical interconnects used to communicate data within a processor core and between different cores. In addition to that, the electrical interconnects can contribute for more than half of the heat dissipated in processors. One of the solutions is to use optical interconnects, thanks to its speed capabilities. A whole optical system is to be built within the processor to exploit this advantage. All the components in this system should be able to pass the power and footprint checkpoints required by the electronics counterpart. In this work we focus on building an optical modulator that can pass these checkpoints. A plasmonic mach zehnder modulator (MZM) is investigated. Plasmonics has the ability to confine light in nanostructures, and in turn, enhance the light-matter interaction. Mach zehnder modulators consume low power, have good bandwidth and robustness. Orthogonal junction coupler is used to couple light from silicon waveguides directly in and out of the modulator, without the need for long tapers. Nano silver triangles are added at the splitter and combiner to decrease the reflections and enhance the coupling. A nonlinear polymer is used that exhibits Pockels effect, to create the destructive interference effect on applying voltage. 15.8 dB extinction ratio, 3.38 dB insertion loss was reached at a voltage-length product of 47 V and 41 fJ bit-1 energy consumption. Plasmonic mach-zehnder modulator with orthogonal junction coupler are more efficient than taper coupler.

10100-77, Session PWed

Fabrication of silver nano trees for SERS application

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The surface-enhanced Raman scattering (SERS) active substrates with high enhancement factor are required to detect trace concentration of biological or organic molecules by using SERS techniques. This work presents the results of the detection of trace concentration of pyridine by using silver nanotrees (AgNTs) that were deposited on silicon. The different densities of AgNTs were fabricated by electroless deposition on silicon wafer by using aqueous solution of HF and AgNO3 with changing etching time. It was observed that with increasing the time of etching the density of the fabricated AgNTs increased at room temperature. The morphology of the fabricated AgNTs was studied by using field emission scanning electron microscope (FESEM). The AgNTs with high branching gave the highest Raman spectrum of pyridine. In addition, the optical properties of the fabricated AgNTs at various etching time have been investigated by using a UV-vis-NIR spectrophotometer. The absorption increased with increasing the etching time due to increasing of branches of silver on silicon substrate.

10100-78, Session PWed

Liquid temperature measurements with a grism and a constant deviation prism

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Temperature sensors could be divided in contact and non-contact. The first class is based on conduction and the second one on radiation energy transmitted in the form of infra-red radiation. Contact sensors are mainly based on electronics. Here we propose the use of two optical methods to measure temperature. They are based on the change of light leaving angle as it exits some prisms. Exiting angle is a function of the refractive index of liquids which in turn depends on the temperature changes. The first method uses a device that consists of two optical components: a hollow prism and a blazed diffraction grating. This ensemble is called Grism. The second method comprises a hollow constant deviation prism (Pellin – Broca). When the Grism is used, and a liquid fills the prism, light with a given wavelength is sent and passes undeviated, or on-axis, through the prism. As liquid temperature changes the light angular deviation also changes because the liquid refractive index changes. A calibration graph can be made considering the angle of deviation as a function of temperature. Regarding the second device, the Pellin – Broca prism, it works as a constant deviation prism. Light enters through a face of the prism and exists at 90o through another face. Again by measuring the angular deviation of the exiting light, as a function of the temperature, it is possible to make a calibration graph. Some liquids have been considered. We will describe the design, fabrication, testing and calibration of both optical devices

10100-80, Session PWed

Nonlinear optical properties of organotetrel chalcogenide-clusters

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Metal chalcogenide clusters show a large variety of physical properties. These are ascribed to their diverse assembly of the cluster atoms. Controlling this assembly enables the possibility to design complex electronic landscapes. Hence, such material are expected to show significant nonlinear optical properties.

Recent studies showed that tetrel chalcogenide-based [(RStyrSn)4S6] cluster molecules exhibit an extreme optical nonlinearity that enables white-light generation based on a continuous-wave laser-diode [1]. The white-light generation in this cluster was assigned to the movement of an electron in the electronic ground-state potential of the ligands pi-system.

To verify this statement we systematically investigate the influence of the ligand by changing it from styryl to methyl, phenyl and naphthyl. The extent of the pi-system has significant impact on the optical response, i.e., changing from white-light generation to second-harmonic generation. This is attributed to changes of the long-range order in the solid state of the compound. This order enables phase-matching conditions, thus quenching white-light generation and favouring second-harmonic generation.

Furthermore, the composition of the cluster core is changed by varying the tetrel component. Making the group IV element lighter, e.g., exchanging tin with germanium shifts the absorption edge of the compound and the respective white-light. Further changes to silicon result in enhanced crystallinity, again quenching the white-light generation and promoting second-harmonic generation.

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10100-81, Session PWed

Photocurrent enhancement in nanocoatings of cerium oxide and platinum on black silicon

Pabitra Dahal, Dionisio Pereira, Elangovan Elamurugu, Jaime Viegas, Masdar Institute of Science & Technology (United Arab Emirates)

Silicon surface modification by reactive ion etching creates a forest of silicon micro-spikes and increases surface area of sample. When the spikes' height exceeds the wavelength of incoming light, light is trapped on the surface through multiple pathway scattering and black silicon (bSi) is formed.

Cerium oxide (CeO2) is believed to have good photoactivity, and finds many applications including photoelectrolysis. However, the large band gap limits the efficiency of the water splitting process. We suggest black silicon surfaces as substrates for CeO2 sputter coating to increase photon-material interaction. An additional catalytic layer of platinum is deposited to create highly energetic electrons as a result of plasmonic resonance and enhances incident photon to current efficiency (IPCE). The difference of surface current for laser on and off condition is found to be 32 times more in black silicon substrate than silicon when similar nanolayers were deposited. A 650 nm wavelength laser was used to illuminate the samples with an irradiance of 20 mW/cm2.

The resistance of flat silicon substrate was 11 ? for laser-off state, decreasing to 9 ? when the laser was turned on. On the other hand, the black silicon substrate sample produced higher resistance of 70 ? in dark which decreased to 1.5 ? for laser on state. The significant drop in irradiated resistance was due to the higher photoactivity and photocurrent was observed to increase from 2 ?A to 0.13 mA for off and on state respectively.

10100-82, Session PWed

An innovative single development process for integrated optical Mach-Zehnder interferometer pattern transfer

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Integrated Optical Mach-Zehnder interferometer (IO-MZI) had been widely used for biosensor application. However, the success rate of IO-MZI pattern transfer had been low using the conventional multi-development process. One of the main factors is the particle contamination due to the use of re-used developer bath. In this work, an innovative single development process had been proposed with the use of same set-up. The concept of this method is the estimation of total development time based on the calculated development rate. By doing so, development process can be completed with only one immersion of substrate in the developer bath. Besides, the manipulation of development rate by varying exposure time in this work also had revealed the possibility of manipulation of line-width based on the exposure time. In short, the proposed single development process had increased the success rate of IO-MZI pattern transfer from 30% (multi-development method) to 90%.

10100-83, Session PWed

Double spacing multi-wavelength Brillouin Raman fiber laser of eight-shaped structure utilizing Raman amplifier

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Double spacing eight shaped utilizing Raman amplifier or it can call as Brillouin Raman Fiber laser (BRFL) is one of the solution of deficiency for single spacing fiber laser system. The eight shaped structure has ability to produce lower noise and double spacing signal. The gain medium acting as a nonlinear medium for the generation of Stimulated Brillouin Scattering and also as a nonlinear gain medium for Stimulated Raman Scattering. Raman amplification has advantages to operate in any wavelength band by simply choosing the appropriate pump wavelength. Double spacing or 0.16 nm spacing is one of solution for the single spacing multi-wavelength because of the difficulty of channel de-multiplexing from narrow single spacing in the communication systems. Other that, the limitation of contribution for the communication system implementation make that the advantages of the double spacing range. In this paper, double spacing eight shaped BRFL utilizing Raman amplifier is simulated and demonstrated. As a results, the optimum results is recorded at 22 dBm of RP power at 1540 nm together with Brillouin power of 12 dBm at 1550 nm. These parameters provide high output power and high gain with output coupling ratio at 90%. The highest peak power of Brillouin Stokes is recorded at 29.88 dBm with gain value of 1.23 dB. The average gain values are slightly increase with increment of output coupling ratio. Meanwhile, most stable average gain is recoded at 1550nm which is from 2 km until 7 km of Raman fiber length. Furthermore, at 8km of Raman fiber, average gain achieve the saturation level. It happen when the length of Raman fiber exceed the saturation of Raman gain.

10100-84, Session PWed

Synthesis and electro-optical property of highly efficient phosphorescent red dopants based on modified main ligands

Seoyun Lee, Dong Myung Shin, Hongik Univ. (Korea, Republic of)

Novel red phosphorescent iridium(III) complexes, (DMAP-MQ)Ir(tmd), (DPAP-MQ)Ir(tmd), (TMP-MQ)Ir(tmd) were synthesized for red emitter of the phosphorescent organic light-emitting diodes (phOLEDs). The ligands have sites of both the electron donor and acceptor in a molecule. The main ligands consisted of electron-donors ((dimethylamino) phenyl, (diphenylamino)phenyl, (trimethylphenyl) and electron-acceptor methyl quinoline were synthesized by suzuki coupling reaction. The iridium(III) complexes based on main ligands and 2,2,6,6-tetramethyl-3,5-heptanedione(tmd) ancillary ligand were synthesized by Nonoyama reaction. Their luminescence property was investigated by UV-visible spectroscopy and photoluminescence (PL) spectroscopy. The manufactured phOLEDs were characterized by investigation of current density-voltage-luminance, power efficiency, external quantum efficiency, life time, electroluminescence spectrum. These phosphorescent iridium complexes will be promising candidates for highly efficient red emitters.

10100-85, Session PWed

Optical inspection with biomedical sensing system by using photonic silicon-based semiconductor device

Yao-Chin Wang, Hungkuang Univ (Taiwan) and National Chiao Tung Univ (Taiwan)

The article proposed dual wavelength silicon based photo detector with multi-layer structure, was fabricated and characterized with dual wavelength enhanced operating. The device proposed the dual wavelength response of the silicon based bio-photo-detector. It can be enhanced by introducing thin porous silicon layer as the base region of transistor. The device process of manufacture is suitable in design of visible-light sensitive bio-photo-detectors. The experimental results showed that the dual wavelength responses in the developed devices were enhanced as compared to the silicon-based homo-junction photo-detectors in optical parameters, which indicated that the developed bio-photo-detector showed potential for practical silicon based biomedical device and system applications.

10100-86, Session PWed

On-axis microscopes for x-ray beamlines at NSLS-II

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A series of versatile on-axis X-ray microscopes with large working distances, high resolution and large magnification have been developed for in-situ sample alignment and X-ray beam visualization at beamlines at NSLS-II. The microscopes use reflective optics, which minimizes dispersion, and allows imaging from Ultraviolet (UV) to Infrared (IR) with specifically chosen objective components (coatings, etc.). Currently over seven reflective microscopes have been procured and installed at NSLS2 beamlines. Additional customizations can be implemented providing for example dual-view with high/low magnification, 3-D imaging, long working range, as well asl ruby pressure system measurement.

10101-1, Session 1

Nonlinear optical and multiphoton processes for in situ manipulation and conversion of photons: applications to energy and healthcare *(Keynote Presentation)*

Paras N. Prasad, Univ. at Buffalo (United States)

Chiral control of nonlinear optical functions holds a great promise for a wide range of applications including optical signal processing, bio-sensing and chiral bio-imaging. In chiral polyfluorene thin films, we demonstrated extremely large chiral nonlinearity. The physics of manipulating excitation dynamics for photon transformation will be discussed, along with nanochemistry control of upconversion in hierarchically built organic chromophore coupled-core-multiple shell nanostructures which enable introduce new, organic-inorganic energy transfer routes for broadband light harvesting and increased upconversion efficiency via multistep cascaded energy transfer. We are pursuing the applications of photon conversion technology in IR harvesting for photovoltaics, high contrast bioimaging, photoacoustic imaging, photodynamic therapy, and optogenetics. An important application is in Brain research and Neurophotonics for functional mapping and modulation of brain activities.

Another new direction pursued is magnetic field control of light in in a chiral polymer nanocomposite to achieve large magneto-optic coefficient which can enable sensing of extremely weak magnetic field due to brain waves. Finally, we will consider the thought provoking concept of utilizing photons to quantify, through magneto-optics, and augment - through nanoptogenetics, the cognitive states, thus paving the path way to a quantified human paradigm.

10101-2, Session 1

Optoelectronically active two-dimensional nanomaterial inks *(Invited Paper)*

Mark C. Hersam, Northwestern Univ. (United States)

Two-dimensional nanomaterials have emerged as promising candidates for next-generation electronics and optoelectronics [1], but advances in scalable nanomanufacturing are required to exploit this potential in real-world technology. This talk will explore methods for improving the uniformity of solution-processed two-dimensional nanomaterials with an eye toward realizing dispersions and inks that can be deposited into large-area thin-films [2]. In particular, density gradient ultracentrifugation allows the solution-based isolation of graphene [3], boron nitride [4], montmorillonite [5], and transition metal dichalcogenides (e.g., MoS2, WS2, MoSe2, and WSe2) [6] with homogeneous thickness down to the atomically thin limit. Similarly, two-dimensional black phosphorus is isolated in organic solvents [7] or deoxygenated aqueous surfactant solutions [8] with the resulting phosphorene nanosheets showing field-effect transistor mobilities and on/off ratios that are comparable to micromechanically exfoliated flakes. By adding cellulosic polymer stabilizers to these dispersions, the rheological properties can be tuned by orders of magnitude, thereby enabling two-dimensional nanomaterial inks that are compatible with a range of additive manufacturing methods including inkjet [9], gravure [10], screen [11], and 3D printing [12]. The resulting printed two-dimensional nanomaterial structures show promise in several applications including photodiodes [13], anti-ambipolar transistors [14], gate-tunable memristors [15], and heterojunction photovoltaics [16].

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10101-4, Session 1

Annealing-induced phase transition in zinc phthalocyanine ultrathin films

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We report the evidence of post-annealing-induced phase transition in zinc phthalocyanine (ZnPc) ultrathin (~20 nm) films upon annealing at 200 °C. The signatures of phase transition are observed in their morphological, structural, and ultrafast spectroscopic properties. Due to kinetical constraint, annealing-induced phase transition in the ZnPc thin films of thickness lesser than 100 nm is rarely observed, but the influence of thickness on the phase transition is still of fundamental interest. In this work, we prepared the ZnPc ultrathin films with nominal thickness of 20 and 50 nm and observed a clear evidence of phase transition when they are annealed at temperatures greater than 200 °C. It is known that the visible absorption band (Q-band) of ZnPc is composed of four subbands. Although there have been several reports on the redshift and the relative change of intensity of subbands depending on the geometry and the crystalline structures, the transient behavior of these subbands associated with the dynamics of excited state is still not well known. Therefore, in this work we redefine the role of the lowest-energy subband in the excited state dynamics during the phase transition and its relation with the structural transformation. In the study of X-ray diffraction (XRD) and ultrafast spectroscopy, long beta-phase nanorods are found to have a very high crystallinity and its long-range character was acquired through the increase of tilt angle and the deformation of planar disk, which distinctively enhance intra- and intercolumnar interactions.

10101-53, Session 1

Random optical media based on hybrid organic-inorganic nanowires: multiple scattering, field localization, and light diffusion *(Invited Paper)*

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Random optical media (ROM) are a novel class of photonic materials characterized by a disordered assembly of the elementary constituents (such as particles, wires and fibers), that determines unique scattering, absorption and emission properties. The propagation of light in ROM is affected by the size and optical properties (refractive index, absorption and emission wavelengths) of their components, as well as by the overall 3-dimensional architecture. So far, most of the investigated ROM have been realized using liquid dispersions or bulk samples embedding colloidal nanoparticles or porous systems. While nanowire-based ROM are poorly investigated, such materials can feature new optical effects related to the elongated shape of their building blocks and to their light-transport properties. Here we report on the fabrication and on the morphological and spectroscopic characterization of hybrid organic-inorganic nanowires, realized by doping polymers with dielectric nanoparticles. We investigate light diffusion and multi-scattering properties of 3-dimensional ROM formed by organic and hybrid nanowires, as well as field localization in 2-dimensional networks. The influence of nanowire geometry and composition on the scattering properties is also discussed.

10101-5, Session 2

Biphotonic probes for NIR in-vivo biophotonics *(Invited Paper)*

Chantal Andraud, Ecole Normale Supérieure de Lyon (France)

No Abstract Available

10101-6, Session 2

Interactions of photochromes with DNA *(Invited Paper)*

Katarzyna Matczyszyn, Marco Deiana, Ziemowit Pokladek, Marta Ziemianek, Joanna Olesiak-Banska, Piotr Mlynarz, Marek Samoc, Wroclaw Univ. of Science and Technology (Poland)

Studies of the interactions between dye molecules and nucleic acids are crucial for any applications of those dyes for imaging or manipulating DNA and are therefore a subject of our interest [1-3]. Intercalation or groove binding can lead to optical changes which can be used for monitoring the binding processes. Host-drugs complexation can be thus studied by numerous spectrophotometrical methods: UV-Vis absorption, fluorescence, circular dichroism. Analysis of the induced spectral effects reveals considerable details about the host-drug binding site size as well as the thermodynamics of the complex formation.

A series of new photochromic aminoazobenzenes was synthesized and their spectroscopic properties were unveiled. An important feature of those new molecules is they high water solubility which is crucial for any biological applications. Moreover, the molecules showed fluorescent properties, unusual for this class of materials, and very interesting from the application as potential markers in biology point of view. It has been found that the cis conformer of aminoazobenzene is thermally stable and the energy of activation (Ea) of the dark cis-trans reaction is 133 kJ/mol which is about 30% higher than that for unsubstituted azobenzene and results in 4 days of the thermal recovery up to 50% of the trans form at room temperature.

The azoderivatives studied may be used for stabilization and destabilization of the B-DNA secondary structure caused by the photochromic reaction induced in situ by light. This photo-triggered process is fully reversible and could be a pathway to control a broad range of biological processes. Moreover, we found that the azoderivative substituted with two polyaminochains in the para-positions of azobenzene exhibited a higher DNA-binding constant than the monocationic molecule (with just one polyamine chain) pointing out that the number of positive charges along the polyamines chain plays a pivotal role in stabilizing the photochrome-DNA complex.

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10101-7, Session 2

Chromophore influence on DNA compactisation *(Invited Paper)*

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Our recent research results showed that DNA chains undergo a compactisation when DNA solutions are doped with different chromophores. In this paper we will present our attempt to model this behaviour in order to predict the DNA solutions characterisation.

10101-8, Session 2

An optically transparent, flexible, patterned and conductive silk biopolymer film

Muhammad Umar, Kyungtaek Min, Ajou Univ. (Korea, Republic of); Sunghwan Kim, Ajou Univ (Korea, Republic of)

Transparent, flexible, and conducting films are of great interest for wearable electronics. For better biotic/abiotic interface, the films to integrate the electronics components requires the patterned surface conductors with optical transparency, smoothness, good electrical conductivity, along with the biofriendly traits of films. We focus on silk fibroin, a natural biopolymer extracted from the Bombyx mori cocoons, for this bioelectronics applications. Here we report an optically transparent, flexible, and patterned surface conductor on a silk film by burying a silver nanowires (AgNW) network below the surface of the silk film. The conducting silk film reveals high optical transparency of ~80% and the excellent electronic conductivity of ~15 Ω/sq, along with smooth surface. The integration of light emitting diode (LED) chip on the patterned electrodes confirms that the current can flow through the transparent and patterned electrodes on the silk film, and this result shows an application for integration of functional electronic/opto-electronic devices. Additionally, we fabricate a transparent and flexible radio frequency (RF) antenna and resistor on a silk film and apply these as a food

sensor by monitoring the increasing resistance by the flow of gases from the spoiled food.

10101-9, Session 3

Origin and control of emitting dipole orientation of phosphorescent dyes in organic light-emitting diodes *(Invited Paper)*

Jang-Joo Kim, Chang-Ki Moon, Kwon-Hyun Kim, Seoul National Univ. (Korea, Republic of)

Phosphorescent iridium complexes have long been thought to have random orientation when doped in an emitting layer due to their octahedron structures. Recently, however, some heteroleptic iridium complexes have been reported to have preferred emitting dipoles orientation (EDO) along horizontal direction (parallel to substrates). The outcoupling efficiency of the emitted light from the horizontally oriented emitting dipoles in an OLED can reach 45% which is much higher than isotropically oriented transition dipoles.

In this talk, we will present that the preferred EDO of Ir complexes in OLEDs originates from the preferred direction of the triplet transition dipole moments and the strong supramolecular arrangement with host molecules. The EDO is influenced by many factors which can be summarized as follows: (1) Heteroleptic iridium complexes are more likely to have preferred orientation in host materials than homoleptic iridium complexes. (2) There is a linear correlation between the EDO in films and the orientation of the transition dipole moments against the C2 axis of the heteroleptic Ir complexes. (3) The EDO of heteroleptic Ir-complexes varies from horizontal to isotropic, or even to vertical direction depending on host molecules. (4) The preferred molecular orientation of the host molecules does not induce the preferred molecular orientation of the dopant molecules.

Finally high efficiency OLEDs with external quantum efficiencies over 35% will be presented using Ir and Pt based phosphorescent dyes possessing highly oriented emitting dipoles and high photoluminescent quantum yields.

10101-10, Session 3

white light emission from an exciplex interface with a single emitting layer

Wilson Bernal, Enrique Perez-Gutierrez, Centro de Investigaciones en Óptica, A.C. (Mexico); Andres Agular, Instituto de Quimica, Univ. Nacional Autónoma de México (Mexico); J. Oracio C. Barbosa G., Jose L. Maldonado, Marco Antonio Meneses-Nava, Mario A. Rodriguez Rivera, Centro de Investigaciones en Óptica, A.C. (Mexico); Braulio Rodriguez, Instituto de Quimica, Univ. Nacional Autónoma de México (Mexico)

Efficient solid state lighting devices based in inorganic emissive materials are now available in the market meanwhile for organic emissive materials still a lot of research work is in its way. [1,2] In this work a new organic emissive material based on carbazole, N-(4-Ethynylphenyl) carba-zole-d4 (6-d4), is used as electron-acceptor and commercial PEDOT:PSS as the electron-donor to obtain white emission. Besides the HOMO-LUMO levels of materials the white emission showed dependence on the films thicknesses and applied voltages. In here it is reported that by diminishing the thickness of the PEDOT:PSS layer, from 60 to 35 nm, and by keeping the derivative carbazole layer constant at 100 nm the electro-luminescence (EL) changed from emissive exciton states to the mixture of emissive exciton and exciplex states. [3] For the former thicknesses no white light was obtained meanwhile for the later the EL spectra broadened due to the emission of exciplex states. Under this condition, the best-achieved CIE coordinate was (0.31,0.33) with a driving voltage of 8 V. To lower the driving voltage of the devices a thin film of LiF was added between the derivative of carbazol and cathode but the CIE coordinates changed. The best CIE coordinates for this case were (0.29, 0.34) and (0.32, 0.37) with driving voltage of about 6.5 V.

References

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10101-11, Session 3

The advantages of aluminum plasmonics for the performance of organic light emitting diodes

Manuel Auer-Berger, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Veronika Tretnak, Karl-Franzens-Univ. Graz (Austria); Franz-Peter Wenzl, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Emil J. W. List-Kratochvil, Humboldt-Univ. zu Berlin (Germany); Joachim Krenn, Karl-Franzens-Univ. Graz (Austria)

While emitters based on thermally activated delayed emission (TADF) allow for a realization of OLEDs with an internal quantum yield close to unity, the issue of efficient light extraction and hence a high external quantum yield still represents a major obstacle on the path to highly efficient OLEDs. As a cost-efficient approach to overcome this bottleneck, in this contribution we discuss the integration of aluminum nanodisc arrays into solution-processed OLEDs. Tuning the sizes of the discs and the lattice constants allows a perfect overlap of the surface lattice resonances of the arrays with the respective emitters in the given dielectric media. Emission quenching of the emitters is avoided by a direct integration of the nanodiscs into the hole transport layers of the OLEDs. In combination with a detailed lifetime analysis and detailed studies on the electroluminescence characteristics of the OLEDs, we give a comprehensive discussion on the impact of the nanodisc arrays on the performance of phosphorescent- as well as TADF OLEDs.

10101-12, Session 3

Enhancing light extraction efficiency in MDMO-PPV based OLEDs by incorporating 250 nm SiO2-colloidal crystals

Juan C. Salcedo-Reyes, Pontificia Univ. Javeriana, Cali (Colombia)

In this work, an improvement in light extraction efficiency from MDMO-PPV based OLEDs by using colloidal crystals is demonstrated. The optimal SiO_2 sphere diameter for the colloidal crystal was determined taking into account the dispersion relation of the system formed by a FCC colloidal crystal infiltrated with the luminescent polymer MDMO-PPV calculated by the Plane Wave Expansion Method (PWEM). The method for elaborating such a polymer layer with a photonic crystal beneath by spin coating was proved and patented. Therefore, devices with the structure ITO/PDOT/MDMO-PPV + SiO_2 colloidal crystal/Ag were elaborated. Compared with standard OLEDs containing a single MDMO-PPV layer, the external quantum efficiency, as evaluated from the electroluminescent spectrum and illumination versus current characteristics of both devices, shows a significant increment for the modified devices with a colloidal crystal matrix within the electroluminescent MDMO-PPV layer.

10101-52, Session 3

Light coupling in polymer nanofibers: from single-photon emission to random lasing *(Invited Paper)*

Andrea Camposeo, Istituto Nanoscienze (Italy); Michele Gaio, King's College London (United Kingdom); Maria Moffa, Istituto Nanoscienze (Italy); Martina Montinaro, Univ. del Salento (Italy); Marta Castro-Lopez, King's College London (United Kingdom); Vito Fasano, Univ. del Salento (Italy); Riccardo Sapienza, King's College London (United Kingdom); Dario Pisignano, Univ. del Salento (Italy)

The understanding of the phenomena underlying the interaction of photons with dielectric, metallic and hybrid micro- and nano-structures and the development of advanced fabrication tools have paved the way to the realization of complex, nanostructured photonic structures, with tailored and exotic absorption end emission properties. Among such nanostructured materials, polymer nanofibers have intriguing and specific properties: they can embed molecular and quantum dot light sources, they can transport light among distant emitters and they can be arranged in 2-dimensional and 3-dimensional architectures in a controlled fashion, forming complex networks of interacting light emitters. However, coupling of light with polymer nanofibers depends on many variables, being often limited by the arrangement and positioning of the nanoscale light-sources, and by the fiber geometry. Here we report on the fabrication of active polymer nanofibers with improved surface properties and controlled geometry by electrospinning. Polarization and momentum spectroscopy of light emitted by molecular compounds and single quantum dots embedded in electrospun polymer fibers, evidence that efficient, nanostructured photon sources with targeted polarization and coupling efficiency can be realized in nanofiber-based photonic environments.

10101-14, Session 4

Charge transport in quasi-one-dimensional and two-dimensional [pi]-conjugated polymers with small carrier effective masses *(Invited Paper)*

Jean-Luc Brédas, Georgia Institute of Technology (United States)

In this presentation, we will discuss the results of recent electronic-structure calculations and molecular-dynamics simulations on:

(i) quasi-one-dimensional ϖ-conjugated polymer chains based on alternating donor and acceptor moieties or on all-acceptor moieties; in particular, we will describe the origin of the large electronic couplings that can be found along the backbones of some of these polymers, which leads to very small charge-carrier effective masses and large mobilities; and

(ii) two-dimensional ϖ-conjugated polymer networks (covalent organic frameworks); here, we will detail how the charge-carrier effective mass evolves as we move from quasi-one dimension to two dimensions.

10101-15, Session 4

Nanostructured organic and hybrid semiconductor lasers *(Invited Paper)*

Ifor D. W. Samuel, Univ. of St. Andrews (United Kingdom)

The strong absorption, high photoluminescence quantum yield and broad spectra of conjugated polymers make these materials attractive candidates for laser materials. Feedback can be conveniently applied using a grating to make a distributed feedback laser, and the grating can be used to shape the emission from the polymer. This talk will present three main results. The first is a simple way of making polymer lasers by solvent imprint lithography. The second is the use of grating design to make unusual laser beams that may have vorticity. The third is a single mode perovskite laser which will be compared with polymer lasers.

10101-16, Session 4

Time-resolved measurement of intramolecular photoinduced electron transfer processes in perylene diimides

Robin Carl Döring, Eduard Baal, Jörg Sundermeyer, Philipps-Univ. Marburg (Germany); Sangam Chatterjee, Philipps-Univ. Marburg (Germany) and Institute of Experimental Physics I, Justus-Liebig-Univ. Giessen (Germany)

Perylene-3,4,9,10-tetracarboxylic acid (PTCDA) and respective derivatives (e.g. perylene diimide - PDI) are widely used as dyes but also for device applications such as organic field effect transistors or in organic photovoltaics. Due to their intrinsically high quantum efficiencies they are also used as spectroscopic standards. One major drawback of these materials is their low solubility in organic solvents which can be addressed by long alkyl substitutions.

When introducing a tertiary amine into the molecule a mechanism known as photoinduced electron transfer (PET) can occur. Here, following an optically excited HOMO-LUMO transition of the core, an electron from the electron lone pair of the amine is transferred to the HOMO of the perylene core. Hence, radiative recombination is disallowed and photoluminescence effectively quenched.

Here, we perform a systematic study of the distance dependence of the PET by introducing alkyle groups as spacer units between PDI core and the tertiary amine. Dynamics of the PET are extracted from ultrafast time-resolved photoluminescence measurement data.

A rate equation model, simulating a three level system, reveals rate constant of the back electron transfer, otherwise not accessible with our experimental methods. Assuming a Marcus model of electron transfer, electronic coupling strength between the electronic states involved in the respective transitions can be calculated. In addition to the distance dependence, the effects of protonation and methylation of the the tertiary amine units are studied.

10101-17, Session 4

Carrier dynamics in pentacene-perfluropentacene heterocrystals

Andre Rinn, Tobias Breuer, Greogor Witte, Philipps-Univ. Marburg (Germany); Sangam Chatterjee, Philipps-Univ. Marburg (Germany) and Institute of Experimental Physics I, Justus-Liebig-Univ. Giessen (Germany)

Aromatic molecules are among the most promising materials in the field of organic optoelectronic due to the favorable properties of the delocalized ?-electron system present in those molecules. One of the most studied systems in this material class is the planar molecule of pentacene. An interesting application for pentacene is the incorporation into a donor-acceptor heterojunction in combination with its perfluorinated counterpart. Such samples may be deposited as intermixed blends (molecular alloys) or as alternating layered stacks. The out-of-plane delocalized ?-electron systems cause significant intermolecular coupling, even enabling the formation of charge-transfer excitons across heterointerfaces. Hence, studying this model system forms the optimal platform to investigate excitation transfer and charge separation in organic solar cells.

We present a comprehensive study of the optical properties of pentacene -perfluoropentacene heterosystems. The samples are grown as crystalline thin films in different molecular configurations: either layered or as intermixed blends, both, in standing and lying molecular orientation. Time resolved luminescence and linear absorption spectroscopy are performed to obtain the carrier dynamics of the charge transfer states and response of the pure materials. The influence of different packing motifs on the optical properties is investigated, revealing a radiationless long-range energy transfer in addition to the local occupation of charge-transfer states.

10101-18, Session 5

Surface-confined supramolecular self-assembly: towards nano-optics on graphene *(Invited Paper)*

André-Jean Attias, Ping Du, David Kreher, Fabrice Mathevet, Univ. Pierre et Marie Curie (France); Sylvain Le Liepvre, Fabrice Charra, Commissariat à l'Énergie Atomique (France)

In view of the demanding forthcoming applications in nanooptics, it is of prime interest to create functions out-off the plane and to fully exploit the room above the substrate. Accessing the dimension perpendicular to the substrate is so a mandatory step to achieve the decoupling from conducting substrate. Here we present a series of 3D organic building blocks able to self-assemble on flat sp2-carbon based substrates like graphene and expose a chromophore decouled from the surface. The chromophores range from fluorescent dyes to photoswitchable molecules. We will present the optical properties in solution as well as the properties of the self-assembled functional monolayers on flat sp2-carbon based substrates. The first fluorescent molecular self-assembly on graphene will be reported

10101-19, Session 5

Single molecule-level study of donor-acceptor interactions and nanoscale environment in blends

Nicole Quist, Rebecca Grollman, Jeremy Rath, Alexander Robertson, Oregon State Univ. (United States); Michael Haley, Univ. of Oregon (United States); John Anthony, Univ. of Kentucky (United States); Oksana Ostroverkhova, Oregon State Univ. (United States)

Organic semiconductors have attracted considerable attention due to their applications in low-cost (opto)electronic devices. The most successful organic materials for applications that rely on charge carrier generation, such as solar cells, utilize blends of several types of molecules. In blends, the local environment strongly influences exciton and charge carrier dynamics. However, relationship between nanoscale features and photophysics is difficult to establish due to the lack of necessary spatial resolution. We use functionalized fluorinated pentacene (Pn) molecules as single molecule probes of intermolecular interactions and of the nanoscale environment in blends containing Pn donor and acceptor molecules. Single Pn donor (D) molecules were imaged in PMMA in the presence of acceptor (A) molecules using wide-field fluorescence microscopy. Two sample configurations were realized: (i) a fixed concentration of Pn donor molecules, with increasing concentration of acceptor molecules (functionalized indenofluorene or PCBM) and (ii) a fixed concentration of acceptor molecules with an increased concentration of the Pn donor. The D-A energy transfer and changes in the donor emission due to those in the acceptor-modified polymer morphology were quantified. The increase in the acceptor concentration was accompanied by enhanced photobleaching and blinking of the Pn donor molecules. To better understand the underlying physics of these processes, we modeled photoexcited electron dynamics using Monte Carlo simulations. The simulated blinking dynamics was then compared to our experimental data, and the transition rates were determined and related to the changing nanoscale environment. Our study provides insight into evolution of nanoscale environment during the formation of bulk heterojunctions.

10101-20, Session 5

Graphene and silver-nanoprism dispersion for printing optically-transparent electrodes

Dogan Sinar, George K. Knopf, Western Univ. (Canada)

Optically transparent electrodes are used for bioelectronics, touch screens, visual displays, and photovoltaic cells. Although the conductive coating for these electrodes is often composed of indium tin oxide (ITO), indium is a very expensive material and thin ITO films are relatively brittle compared to conductive polymer or graphene thin films. An alternative highly conductive optically transparent thin film based on a graphene (Gr) and silver-nanoprism (AgNP) dispersion is introduced in this paper. The aqueous Gr ink is first synthesized using carboxymethyl cellulose (CMC) as a stabilizing agent. Silver (Ag) nanoprisms are then prepared separately by a simple thermal process which involves the reduction of silver nitrate by sodium borohydride. The Gr-AgNP dispersion is then deposited on optically transparent glass and polyimide substrates using an inkjet printer with a HP6602A printhead. After printing, these thin films are thermally treated to increase electrical conductivity by decomposing CMC particles. The thermal process also makes the conductive film hydrophobic. Unlike most nanoparticles, these Ag nanoprisms have large surface areas (>1000 sq nm) and as a result provide more efficient injection of free carriers to the Gr layer. Preliminary experiments demonstrate that the Gr-AgNP films on glass substrates exhibit high conductivity at 70% transparency (550 nm). Additional tests on the Gr-AgNP thin films printed on polymide substrates show mechanical stability under bending with minimal reduction in electrical conductivity or optical transparency. Finally, a simple large-area optically transparent heating element is to fabricated and tested to demonstrate the potential of printed Gr-AgNP thin films.

10101-13, Session 6

Spectroscopic Investigation of Squaraine Dyes

Giuseppe Maria Paternò, Istituto Italiano di Tecnologia (Italy); Simone Galliano, Nadia Barbero, Claudia Barolo, Raffaele Borrelli, Guglielmo Lanzani, Univ. degli Studi di Torino (Italy) and Ctr. For Nanostructured Interfaces and Surfaces, Univ. degli Studi di Torino (Italy); Francesco Scotognella, Politecnico di Milano (Italy)

Squaraine dyes (SQs) represent a class of functional molecules with a typical electron Donor-Acceptor-Donor molecular framework, and exhibiting strong light absorption and emission properties. These advantageous features coupled with the possibility to cover a large range of wavelengths (visible-near IR) via the versatility of chemical synthesis, has made these molecules appealing for a number of applications, such as biolabeling and organic/hybrid photovoltaic.

In recent years, the photodynamic of these molecules has been studied extensively, and has been seen to be strongly dependent on the electron-donating properties of the donor blocks and on the molecular symmetry of the dye. For instance, it has been observed that the photoexcitation deactivation occurs via two concerted routes: i) an intramolecular vibrational energy redistribution (IVR) involving a trans-cis photoisomerisation and ii) an intramolecular charge transfer (ICT) [1].

In this study, we performed ultrafast transient absorption in the femto/nanosecond time-domain to elucidate the role of the interplay between the electronic and steric properties of the side-group in determining

the photodynamics of three SQs dyes, observing that that the relative magnitude of the two mechanisms can be tuned by exacerbating the steric/electronic features of the side group.

[1] De Miguel et al.,J. Phys. Chem. C, 2012, 116 (22), pp 12137–12148

10101-21, Session 6

Planar heterojunction perovskite solar cells fabricated by wet process *(Invited Paper)*

Tetsuya Taima, Kouhei Yamamoto, Md. Shahiduzzaman, Kanazawa Univ. (Japan)

Hybrid organometal halide perovskites such as methylammonium lead iodide (MAPbI3) are a promising class of cost- and energy-efficient light absorption materials for thin-film photovoltaics. In this work, the preparation and characterization of MAPbI3 nanoparticles (NPs) on TiOx/indium tin oxide glass substrates using a simple spin-coating technique have been investigated. The NPs were prepared by spin-coating solutions of MAPbI3 and the ionic liquid (IL) 1-hexyl-3-methylimidazolium chloride in N,Ndimethylformamide.

Analysis of the resulting spin-coated films revealed that uniform spherical MAPbI3 NPs with an average diameter of 540 nm were homogeneously distributed on the TiOx substrates.

MAPbI3 films with similar crystallinity were observed irrespective of the inclusion of IL, as evident from the X-ray diffraction patterns of the films. However, addition of IL to the spin-coating solution facilitated the formation of homogenous nucleation sites and prevented rapid crystal formation of MAPbI3.

Therefore, the presence of an IL resulted in uniform thin films with good morphology.

10101-22, Session 6

Local heterogeneity and the role of interfaces on hybrid perovskite photovoltaic performance *(Invited Paper)*

David S. Ginger, Univ. of Washington (United States)

Organic/inorganic hybrid perovskite thin films exhibit significant heterogeneity in local non-radiative recombination rates when grown by many different routes. In this talk, we will describe both confocal fluorescence lifetime imaging microscopy and scanning-probe microscopy studies that help elucidate the origins of this local heterogeneity in terms of composition and surface defects. Through a combination of scanning-probe microscopy, light-beam induced current, and confocal photoluminescence imaging we show that common electron and hole extracting contacts also induce heterogeneous non-radiative recombination losses into perovskite devices. By using surface ligand treatments, we are able to tailor the materials properties to obtain carrier lifetimes and PL intensities in thin films approaching those in single crystals, opening the way for these materials to approach the Shockley-Queisser limit.

10101-23, Session 6

Organometallic perovskite solar cells: a study of temperature effect

Mingkui Wang, Huazhong Univ. of Science and Technology (China)

It is highly desirable to develop new solar cells to operate at temperatures higher and lower than standard operational conditions for space and near space applications in future. Herein, we communicate an experimental investigation on temperature-dependent photovoltaic efficiency for perovskite solar cells based on mesoscopic TiO2/Al2O3/NiO/carbon architecture. This perovskite device shows impressive 5% power conversion efficiency at low temperature of 80 K. Therefore, the perovskite solar cells can be precisely characterized in a wide temperature range, which enables unequivocal identification of the contribution of CH3NH3PbI3 perovskite to construction of the built-in electric field, and thus, the temperature dependent photovoltaic parameters. The latter, particularly the open-circuit voltage, shows a strong dependence on the dielectric constant of CH3NH3PbI3.

10101-24, Session 6

Experimental and modeling studies of charge generation and dynamics in fullerene-based organic photovoltaics

Liang Xu, Jian Wang, Trey B. Daunis, The Univ. of Texas at Dallas (United States); Manuel de Anda Villa, Univ. of Texas at Dallas (United States); Yun-Ju Lee, Anton V. Malko, Julia W. P. Hsu, The Univ. of Texas at Dallas (United States)

The fullerene-based organic photovoltaic devices (OPVs) containing very minute amounts of polymer or small molecule “donor” materials have recently attracted intensive research interest because its performance is not limited by the trade-off between short-circuit current density (Jsc) and open-circuit voltage (Voc), unlike bulk heterojunction OPVs. However, the mechanisms of photocurrent generation, which always shows a non-monotonic dependence on donor concentration, and the origin of high Voc, which is still under debated between the Schottky-junction framework and the result of reduced non-geminate recombination, are not understood in this novel OPVs system. To understand the Jsc and Voc behaviors, we study a series of fullerene PC71BM based OPVs with varying P3HT concentrations between 0 and 50 wt.%. External quantum efficiency, time-resolved photoluminescence, UV-visible absorption, impedance spectroscopy, X-ray diffraction, charge extraction together with 1D transfer matrix method and 1D drift-diffusion SCPAS simulations are employed. The Jsc behavior is well explained through analytical and quantitative investigations of three loss mechanisms: diffusion limited exciton relaxation, geminate recombination during exciton dissociation, and non-geminate recombination during charge transport. In addition, while Voc maintains high (~ 0.9V) at lower P3HT concentration, an abrupt decrease of Voc is observed at 35 wt.% P3HT inclusion, indicating a transition between two different mechanisms that govern Voc. We further probe this transition through annealing temperature, which effectively change the film morphology, especially the P3HT aggregation. Also, distinctive behaviors of frequency-dependent capacitance are observed, which are correlated with the low hole mobilities in these devices. The effects of charge recombination and transport on Voc will be discussed.

10101-25, Session 6

Charge carrier dynamics at the pentacene-C60 interface

Robin Carl Döring, Andrea Karthäuser, Tobias Breuer, Gregor Witte, Philipps-Univ. Marburg (Germany); Sangam Chatterjee, Philipps-Univ. Marburg (Germany) and Institute of Experimental Physics I, Justus-Liebig Univ. Giessen (Germany)

Organic molecular solids feature various properties considered advantageous for next-generation photovoltaic devices such as mechanical flexibility and ease of fabrication by, e.g., large-scale and large volume printing. Additionally, Singlet-Exciton Fission may allow surpassing the Shockley-Queisser limit. Here, one photoexcited singlet-type exciton decays into two triplet-type excitons, effectively doubling the number of excited charge carriers. Hence, above-unity quantum efficiencies may be achieved in photovoltaics and have been reported in for example, pentacene (PEN) –C60 heterojunctions.

Here, we study the carrier dynamics at well-defined PEN-C60 interface model systems by time-resolved photoluminescence spectroscopy experiments for different excitation photon energies. Thereby, we disentangle charge transfer and excitation dynamics, i.e., injection, transport, dissociation, and extraction.

The photoluminescence spectra reveal two distinct transition energies associated with charge-transfer (CT) states expected from photoelectron spectroscopy experiments. These long-lived transitions show a clear dependence on excitation energy, corroborating the proposed CT transitions and revealing the fact that carriers need to be created in both individual constituents for CT transitions to be observable.

Additionally, the C60 photoluminescence efficiency strongly quenches for increasing PEN coverage while the lifetime is drastically enhanced yielding strong evidence for an electron transfer between the PEN ground state and C60 when only the latter is photoexcited.

10101-28, Session 7

Photothermal effect in conductive polymer layers for structural conversion into a complex 3D structure *(Invited Paper)*

Eunkyoung Kim, HanWhuy Lim, Jongbeom Na, Yonsei Univ. (Korea, Republic of)

The conversion of photons to heat in the conductive polymer films causes local heating to increase temperature at the light exposed area. The resultant heat can be converted into other type of energy such as electrical, mechanical, or chemical energy. In particular, photothermal effect in conductive polymer layers could be used for structural changes of the 2D structures into a complex three-dimensional (3D) structure. Herein we report the preparation of photothermal conductive polymer layers (CPL) and the integration of CPLs into a 2D structured film, to optimize not only the light-to-heat but also 2D-to-3D structural conversion.

10101-29, Session 7

Photoanisotropy in polarization-sensitive polymer materials based on the media with covalently-bounded components

Irakli Chaganava, Barbara N. Kilosanidze, George Kakauridze, Institute of Cybernetics (Georgia); Luis Oriol, Milagros Piñol, Alfonso Martinez-Felipe, Institute of Materials Science of Aragon, Univ. de Zaragoza (Spain) and Consejo Superior de Investigaciones Científicas (Spain)

Our earlier researches of organic polarization-sensitive materials on the basis of functional azo dyes introduced into the polymer showed that effectiveness of such media essentially depends on integration of the molecules of their components. This work presents the results of researches of the side-chain azopolymers, synthesized by us, as well as the commercial ones, in which the molecules of light absorbing components are immobilized in the polymer matrix by means of singular strong covalent bond. It is shown that in such polarization-sensitive materials the level of induced anisotropy is much higher than in the materials with identical composition, but not containing strong intermolecular bonds between the components. In addition, in the studied photo-sensitive media a stronger vector polyphotochromic effect is observed that we have been revealed earlier. The work shows that even one of the most highly effective polarization-sensitive compositions comprising solid solution of bis-azo dye in the polymer matrix yields to some media based on side-chain azopolymers that were obtained and studied by us, with regard to vector polyphotochromism or photo anisotropy effects.

10101-30, Session 7

Fungi-derived pigments as sustainable organic (opto)electronic materials

Robert Harrison, Alexander Quinn, Genevieve Weber, Brian Johnson, Jeremy Rath, Vincent Remcho, Sara Robinson, Oksana Ostroverkhova, Oregon State Univ. (United States)

Organic pigments derived from natural products have recently attracted attention, exhibiting extraordinary environmental stability combined with high (photo)conductivity, in spite of their molecular structure not having a fully conjugated core. Pigments derived from fungi represent a sustainable and unexplored resource for organic (opto)electronics. We present photophysical and optoelectronic properties of xylindein and other fungi-derived organic pigments. Xylindein specifically is a blue-green quinone pigment secreted by the wood-staining fungi Chlorociboria aeruginosa and C. aeruginascens, which currently is not possible to synthesize, yet can be readily derived from liquid cultures. A particularly important aspect of the xylindein photophysics is its ability to form both intermolecular and intramolecular hydrogen bonds. The interplay of these interactions depends on the environment, which we quantified using measurements of optical absorption and time-resolved photoluminescence of xylindein in various solvents and pH buffers. The (opto)electronic properties of xylindein were measured in thin films deposited from solution onto substrates with coplanar electrodes. From space-charge limited currents, a lower bound on the charge carrier mobility of 0.2 cm2/(Vs) was determined in amorphous xylindein films. The films also exhibited photocurrent upon photoexcitation in the ultraviolet and visible wavelength range. Long-term thermal and photostability of xylindein in solution and in devices was characterized, and it considerably exceeded that of traditional organic semiconductors such as pentacene derivatives. Moreover, xylindein is one example of a larger class of hydrogen-bonded fungi-derived pigments. Photophysical properties of other pigments, such as red and yellow pigments derived from Scytalidium cuboideum and Scytalidium ganodermophthorum, respectively, will also be presented.

10101-31, Session 7

Fulvalene compounds with transition metals

Hal Gokturk, Ecoken (United States)

Fulvalene compounds containing various transition metal elements, such as fulvalene diruthenium tetracarbonyl, FvRu2(CO)4 were synthesized in 1990s [1]. Such compounds are getting renewed attention due to their potential to absorb solar energy and store it as a photo-isomer of the compound for an extended period of time.

In this research magnetic interactions between the transition metals in these compounds are investigated. Storage and release of the energy can be controlled by external magnetic means if they exhibit magnetic properties.

The compounds studied are FvRu2(CO)4, FvCo2(CO)4, FvCr2(CO)6, FvMo2(CO)6 and their counterparts without carbonyl ligands. The analysis is carried out by quantum mechanical calculations using the DFT method with B3LYP functional and Pople type basis sets augmented with polarization functions. For each compound, stable ground state conformation and its meta-stable photo-isomer are calculated and the two conformations are compared in terms of energy and magnetic properties.

Results indicate that the compound which contains Ru does not have magnetic properties, but the others exhibit magnetic behavior. Magnetic properties are most pronounced when carbonyl ligands are not present. Stored energy also increases without the carbonyl ligands. Hence removal of the ligands after synthesis is highly desirable.

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10101-32, Session 8

Photoinduced (anomalous) dynamics of functionalized polymer chains: applications for surface relief grating modelling *(Invited Paper)*

Antoni C. Mitus, Michal A. Szczesniak, Tomasz Wysoczanski, Grzegorz Pawlik, Wroclaw Univ. of Science and Technology (Poland)

Recently we have formulated a generic Monte Carlo model for the photoinduced build up of the density grating and surface relief grating (SRG) in a model polymer matrix functionalized with azo-dyes [1]. Mass transport from illuminated to dark places was demonstrated and ascribed to a hypothetical complex dynamics of polymer chains in bond-fluctuation model. In this paper we characterize the motion of single functionalized chains dependent on two factors: intensity of light illumination and its gradient. We report various regimes of diffusion: subdiffusion, normal diffusion and superdiffusion and determine the conditions which promote those motions. The origin of the effect of "fine structure" of SRG close to the maximum of its density is discussed and a simple mechanism of mass transfort which might be responsible for it is proposed. The results provide a deeper insight into the mechanisms responsible for inscription of SRG as well as for single functionalized nanoparticle studies [2].

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10101-33, Session 8

Flexible thin polymer waveguide Bragg grating sensor foils for strain sensing

Jeroen Missinne, Nuria Teigell Benéitez, Gabriele Chiesura, Geert Luyckx, Joris Degrieck, Geert Van Steenberge, Univ. Gent (Belgium)

Waveguides with Bragg gratings realized on a flat substrate are promising for advanced strain sensing since such a planar approach allows precise positioning of the sensors and allows using more complex layouts, e.g. sensors in various well-defined directions. For structural health monitoring, the sensors are ideally embedded inside the structure, e.g. to protect them from the harsh operating environment. Therefore, the sensor foils need to be unobtrusive (very thin and flat) and compatible with the host material.

This paper demonstrates that epoxy-based single mode polymer waveguides with Bragg gratings can be realized in very thin (down to 50 micron) polymer foils which are suitable for strain sensing when integrated inside composite material. The single mode waveguides were fabricated using laser direct write lithography and the gratings were realized using nanoimprint lithography. These steps were performed on a temporary rigid carrier substrate and afterwards the functional layers were released yielding the thin, flexible sensor foils which can be laser-cut to the required dimensions.

The Bragg grating-based polymer waveguide sensor foils were characterized before and after embedding into a glass fiber reinforced polymer (GFRP) composite. As expected, there was a blueshift in the reflection spectrum because of residual strain due to the embedding process. However, the quality of the signal did not degrade after embedding, both for 50 and 100 micron thick sensor foils. Finally, the sensitivity to strain of the embedded sensors was determined using a tensile test and found to be about 1 pm / ?strain.

10101-34, Session 8

Multi-layered fabrication of large-area flexible PDMS waveguides

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Large area mechanically flexible polydimethylsiloxane (PDMS) waveguides can be designed to acts as light collectors, non-planar illuminators or hybrid concentrator-diffuser sheets. The performance of the large area thin PDMS waveguide is a function of the location and geometry of micro-optical structures, thickness and shape of the flexible waveguide, core and cladding material (i.e. refractive indices), and the wavelength of the incident light source. The fabrication of these non-rigid waveguides is complicated because the optical device must be thin (>> 1 cm) and the active surface can range from centimeters to several meters square. The scalable fabrication method described in this paper for creating a multi-layered large area PDMS waveguide combines soft-lithography, closed thin cavity molding, partial curing, and centrifugal casting. Critical to the methodology is the creation of internal micro-optical structures (MOSs) in the monolithic PDMS sheet. These internal MOSs are achieved by building the waveguide layer-by-layer from the bottom up. Each constituent PDMS layer can have the same or a slightly different index of refraction. The active surfaces of each molded layer may be smooth or micro-patterned depending upon the role of optical interface between the adjacent layers. Furthermore, each layer is only partially cured before the next layer is added to ensure complete bonding of the adjoining surfaces. To illustrate this build-by-layers methodology for fabricating complex large area PDMS waveguides a three-layer illuminator with an LED strip embedded on one edge of the flexible waveguide is constructed and tested.

10101-35, Session 8

Polymer optical fibers doped with organic materials as luminescent solar concentrators

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In recent years, photovoltaic energy has attracted a great deal of attention due to its potential as inexhaustible, climate friendly, and ubiquitous energy source. Particularly, increasing the efficiency of solar concentrators in an economical way remains one of the main goals of photovoltaic technology. The use of polymers doped with organic materials appears to be an effective approach as luminescent solar concentrators, both in films and fiber geometry [1,2]. The waveguide structure of the latter ones presents a number of added benefits, such as optical confinement in the core-area and high ratio between surface area and volume, allowing heat dissipation. At the same time, polymer optical fibers have the advantage of been light-weight, thin, and flexible, which eases their manipulation.

In this work, we have carried out an optical characterization of several polymer optical fibers doped with organic materials, from conjugated polymers to organic dyes. A new fiber doped with lumogen orange, manufactured by the authors has also been analyzed. The study includes time-resolved spectroscopy of the luminescence of the different doped fibers and a deep analysis of the light propagation along them. The results obtained have been thoroughly compared, paying special attention to the UV/blue-to-visible light conversion-efficiency.

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in luminescent solar concentrators," Appl. Opt. 49, pp. 1651-1661 (2010).

[2] Y Edelenbosch, O. et al., "Luminescent solar concentrators with fiber geometry," Opt. Express. 21, pp. A503-A514 (2013).

10101-36, Session 8

Multi-recognition organic nanowire barcode

Seokho Kim, Hyeong Tae Kim, Jinho Choi, Ho Jin Lee, Dong Hyuk Park, Inha Univ. (Korea, Republic of)

Generally ϖ-conjugate organic materials have a specific optical characteristics, e. g. luminescence, because they are different such as band structure, kind of atomic, sequence and so on. We made a won-dimensional (1-D) hybrid nano materials which is consisted of heterogeneous organic materials. 1-D hybrid polymer nanostructures (HNS) are stacked up alternately into a single unit. These materials are fabricated in alumina template by electrochemistry method.

We drastically recognized distinct photoluminescence (PL) and raman in single HNs. We used homemade a high resolution laser confocal microscope equipment for nanoscale PL and raman experimental. Furthermore, we attached metal nano particles on to the surface of HNs which are increased a capability of recognition due to plasmon effects. Plasmon effect can be occurred interactions between 1-D HNS and suitable metal nano particles. We controlled degree of plasmon effect by changing kind of metal nano particles.

10101-37, Session 9

Optical properties and thermal stability of EO polymers and waveguides cross-linked with multi-functionalized EO molecules *(Invited Paper)*

Akira Otomo, Isao Aoki, Chiyumi Yamada, Rieko Ueda, Toshiki Yamada, National Institute of Information and Communications Technology (Japan)

Recently developed electro-optic (EO) polymers showing large EO coefficient have attracted considerable attention to applying to high-speed modulators, optical interconnection, electromagnetic wave sensors, THz wave generators and detectors, etc. Thermal stability of EO polymers is one of the critical issues for applying the polymers to practical devices. Cross-linking of polymer is a conventional and promising way to make a thermally stable polymer. However, cross-linking has not been successfully used for waveguide devices because waveguide propagation loss increases significantly after cross-linking and complicated poling process with precisely controlling temperature and time is required. One of the reasons of increasing propagation losses is scattering generated from the cross-linkage sites. Possible source of the scattering is inhomogeneity made by local cross-linking reaction in solidity state of film. We developed a new type of thermally stable polymer that is cross-linked with multi-functionalized EO molecules in solution phase. These polymers have high glass transition temperature (Tg) over 200 °C and show excellent thermal stability. Although the polymers are cross-linked, they are soluble in common solvents for spin coating and can be made into homogeneous films. We will discuss thermal stability and optical properties of the polymers and waveguides, and device fabrication processes using them.

10101-38, Session 9

Effect of surface resistance on electric field poling of nonlinear optical polymers *(Invited Paper)*

James G. Grote, Air Force Research Lab. (United States)

No Abstract Available

10101-39, Session 9

Preparation of temperature-stable electro-optic polymer waveguide modulators

Hiroki Miura, Kazuhiro Yamamoto, Shiyoshi Yokoyama, Kyushu Univ. (Japan)

In this work, we synthesized temperature stable electro-optic (EO) polymers by post-functionalization technique. The EO polymer consists of high molecular hyperpolarizability chromophore based on FTC and CLD derivatives, which are attached to the high glass transition temperature PMMA polymer. The post-functionalization is useful to control the loading concentration of the chromophore in the polymer backbone between 20 and 40 wt%. Therefore, we found the optimum loading of the chromophores to achieve the highest EO activity. Furthermore, we found that the use of adamantly methacrylate can enhance the stability of the EO polymer at elevated temperatures. We analyzed details of the synthesized EO polymers by using the size exclusion chromatography, UV-vis spectroscopy, and Tg and decomposition (Td) analyzers. We fabricated the EO polymer waveguide modulators in order to evaluate EO coefficient (r33), half-wave voltage (Vpi), and temperature stability. The waveguide was prepared by using sol-gel SiO2 cladding layers, ridge waveguide, EO polymer core, and electrodes. All layers were prepared by using the spin coating technique, and ride waveguide was by conventional photolithography technique. After fabrication of the waveguide, the high voltage around 800 V was applied to the electrodes to pole the EO polymer at around Tg. After cooling, the measured Vpi was around 2-4 V, and r33 of 60-80 pm/V at 1550 nm in the waveguides. Because synthesized EO polymers have a high Tg property at around 165-170C and Td of higher than 200C, we measured excellent temporal stability of the waveguide modulator at 85C for 2000 hours.

10101-40, Session 9

Nonlinear optics in organic cavity polaritons *(Invited Paper)*

Kenneth D. Singer, Bin Liu, Case Western Reserve Univ. (United States); Michael Crescimanno, Youngstown State Univ. (United States); Robert J. Twieg, Kent State Univ. (United Kingdom)

Coupling between excitons belonging to organic dyes and photons in a microcavities forming cavity polaritons have been receiving attention for their fundamental interest as well as potential applications in coherent light sources. Organic materials are of particular interest as the coupling is particularly strong due to the large oscillator strength of conjugated organic molecules. The resulting coupling in organic materials is routinely in the strong regime. Ultrastrong coupling between photons and excitons in microcavities containing organic dyes and semiconductors has been recently observed in room temperature. We have studied the coupling between cavity pairs in the ultrastrong regime and found that the high order terms in the modified Jaynes-Cummings model result in broken degeneracy between the symmetric and antisymmetric modes.

The unusually strong coupling between cavity photons and organic excitons dovetail with the robust nonlinear optical responses of the same materials. This provides a new and promising hybrid material for photonics.

We report on measurements of photorefraction in organic cavities containing a derivative of the photorefractive organic glass based on 2-dicyanomethylene-3-cyano-2,5-dihydrofuran (DCDHF).

10101-41, Session 10

Graphene-based organic-inorganic hybrids with optoelectronic and magneto-optic functions *(Invited Paper)*

Kwang-Sup Lee, Sung-Hyun Kim, Juhyoung Jung, Xue-Cheng Teng, Prem Prabhakaran, Hannam Univ. (Korea, Republic of)

Groups around the world are pursuing optoelctronic and magneto-optic properties of graphene-based materials since they hold a lot of promise for future technologies. Quantum dot (QD) decorated graphenic nanohybrids can be candidates for demonstrating energy transfer, while magnetic nanoparticles (MNPs) on graphene give rise to interesting electronic phenomena like magneto-optical effects. Graphene containing MNPs are also good candidates for exploring quantum-hall effect. In medicine these materials have demonstrated applications in bioimaging, drug delivery, photothermal treatment and magnetic resonance imaging. A majority of groups working on QD or MNPs have focused on chemical functionalization methods for making graphene-MNP nanohybrids. We have developed a set of small molecule as well as polymeric ligands for noncovalent self-assembly of nanoparticles on graphene. The ligands contain pyrene as an anchor group for graphene and also thiol or dipamine as anchor groups for QD or MNPs. In this presentation we discuss the synthesis and characterization of these materials and outline some early results regarding exploratory device fabrication involving these materials.

10101-42, Session 10

Additive Manufacturing of Tunable Lenses

Katja Schlichting, Univ. of Applied Sciences Aalen (Germany); Tobias Novak, Aalen University of applied Science (Germany); Andreas Heinrich, Univ. of Applied Sciences Aalen (Germany)

Individual additive manufacturing of optical systems based on 3D Printing offers wide possibilities in design and usage. In addition to the additive manufacturing procedure, the usage of liquid lenses allows further advantages for intelligent optical systems. Our goal is to bring the advantages of additive manufacturing together with the huge potential of liquid lenses.

We produced liquid lenses as a bundle without any further processing steps, like polishing. The lenses were designed and directly printed with a 3D Printer as a package. The design contains the membrane as an optical part as well as the mechanical parts of the lens, like the attachments for the sleeves which contain the oil.

The dynamic optical lenses were filled with an oil. The focal length of the lenses change due to a change of the radius of curvature. This change is caused by changing the pressure in the inside of the lens. In addition to that, we designed lenses with special structures to obtain different areas with an individual optical power. The goal is to use specialized lenses for individual tasks such as the illumination of an object and the capturing of the signal.

We want to discuss the huge potential of this technology for several applications. The lenses could be used for illumination tasks, and in the future, for individual measurement tasks. The main advantage is the individuality and the possibility to create an individual design in order to fulfill the individual requirements for specific applications.

10101-43, Session 10

Change of electric dipole moment in charge transfer transitions of ferrocene oligomers studied by ultrafast two-photon absorption

Aleksander K. Rebane, Montana State Univ. (United States) and National Intitute of Chemical Physics and Biophysics (Estonia); Alexandr Mikhailov, Montana State Univ. (United States); Merle Uudsemaa, National Intitute of Chemical Physics and Biophysics (Estonia); Aleksander Trummal, National Institute of Chemical Physics and Biophysics (Estonia); Thomas M. Cooper, Air Force Research Lab. (United States); Ronald Ziolo, Eduardo Arias, Ivana Moggio, Centro de Investigación en Química Aplicada (Mexico)

Instantaneous two photon absorption (2PA) by organic chromophores and fluorophores is versatile nonlinear-optical photo-physical mechanism and is widely used for biological imaging, fast optical switching and microfabrication. Characterizing the molecular two-photon absorption cross-section, sigma2PA, plays important role because higher value generally means higher efficiency of the corresponding nonlinear process. On the other hand, from the measured sigma2PA one can also garner structure-property relations and other useful information about the underlying photo-physical properties.

It has been demonstrated that in a strongly dipolar chromophore, such as some laser dyes, the peak sigma2PA value of in the lowest-energy S0?S1 transition is directly proportional to the change of the permanent electric dipole moment in that transition, delta mju. This property can be used as a versatile spectroscopic technique to determine the absolute value of delta mju, especially under conditions, where implementation of traditional methods such as Stark shift spectroscopy and solvatochromism may be challenging. Here we apply the 2PA-based technique to study the permanent electric dipole moment in a series of metallo-organic oligomers, comprising either one or two ferrocenes covalently attached to organic moieties of varying conjugation length. We use femtosecond nonlinear transmission method to determine the peak value and the wavelength dependence of sigma2PA in the two lowest-energy transitions and show that the dipole moment change varies in the range, delta mju ~ 3 - 10 D, depending on the length of the moiety and on the number of the ferrocenes (one or two). We also perform DFT calculations that corroborate the picture of charge transfer occurring from the ferrocene towards the organic backbone.

10101-44, Session 10

Additive manufacturing: a new approach to realize complex and unconventional optical components

Andreas Heinrich, Manuel Rank, Hochschule Aalen (Germany); Sangeetha Suresh Nair, Yannick Bauckhage, Phillipe Maillard, University for applied Science Aalen (Germany)

Additive manufacturing allows the production of complex and individualized 3dimensional components. It has established itself in the field of mechanics as an additional manufacturing method. In the production of optical components it offers a high potential as well, since it allows completely new design approaches.

In this paper we report on the realization of complex freeform optics using standard 3D printers. We briefly point out the characteristics of 3D printing and the printing materials. The influence of the layered structure and the

surface roughness on the optical properties is discussed as well as the transmission characteristics of different materials.

In the second part of this paper we address the needed rework of 3D printed optical components. The aim is to obtain a surface finish, which is adequate for optical components. Therefore we apply two different methods. Firstly, robot-based polishing of the components by means of a fluid jet. Secondly, a dip-coating method which allows a faster processing and the rework of complex shapes.

The realization of standard components (e.g. lenses) is not an ideal application for 3D printed optics. The advantage of a 3D printed optic lies in its shape complexity, which is not or not easily feasible with standard methods. This is discussed in the third part of the paper. A complex shaped optical element is discussed, which generates an arbitrary shaped laser line from a laser spot (e.g. needed for optical metrology). Additionally we show how a conventional 3D printer can be used to realize diffractive optical elements.

10101-26, Session PWed

The encapsulation material development of thermal curing method of a dye-sensitized solar cell with silicon resin

Hyun Chul Ki, Seon Hoon Kim, Doo-Gun Kim, Tae-Un Kim, Haeng-Yun Jung, Korea Photonics Technology Institute (Korea, Republic of); Jae-Man Jae-Man, TKHT Co., Ltd. (Korea, Republic of)

Dye-Sensitized solar cell (DSSC) is expected to be one of the next-generation photovoltaics because of its environment-friendly and low-cost properties. However, commercialization of DSSC is difficult because of the electrolyte leakage. We propose thermal curable base on silicon resin and apply a unit cell and large area (200X200mm) dye-sensitized solar cell. The resin aimed at sealing of DSSC and gives a promising resolution for sealing of practical DSSC. In result, the photoelectric conversion efficiency of the unit cell and the module was 5.52% and 5.52%, respectively. In the durability test result, the photoelectric conversion efficiency of the module during 100, 500 and 1,000 hours was 1.34%, 1.32%, 2.53%, respectively. It was confirmed that the photoelectric conversion efficiency characteristics are constant. We have developed encapsulation material of thermal curing method excellent in chemical resistance. A sealing material was applied to the dye-sensitized solar cell and it solved the problem of durability the dye-sensitized solar cell. Sealing material may be applied to verify the possibility of practical application of the dye-sensitized solar cell.

10101-46, Session PWed

Electron transport layer (ETL)-free inverted organic solar cells fabricated with transparent conductive amorphous-IGZO/Ag/IGZO multilayer electrode

Jun Ho Kim, Tae-Yeon Seong, Korea Univ. (Korea, Republic of)

Inverted organic solar cells (OSCs) were fabricated with conventional ITO and optimized amorphous indium gallium zinc oxide (a-IGZO)/Ag/a-IGZO (a-IAI) multilayer thin films and their electrical characteristics were characterized. Both the ITO and a-IAI electrodes had high transmittance at 550 nm. The a-IAI electrodes exhibited higher carrier concentration and lower sheet resistance than the ITO. Electron transport layer (ETL)-free OSCs fabricated with the a-IAI electrode showed much higher PCE than the ETL-free OSCs with the ITO electrode. The buffer layer (ETL)-free OSCs fabricated with the a-IAI electrode showed much higher PCE than the buffer layer-free OSCs with the ITO electrode. The improvement was attributed to the roles of the a-IAI electrode, serving as an ETL and a hole blocking layer. The result indicates that the a-IAI electrode can be used as a promising transparent electrode for the fabrication of cost-effective and simple-process OSCs.

10101-48, Session PWed

Deep-blue light emission with a wide-bandgap naphthalene-derivative liquid organic semiconductor host

Naofumi Kobayashi, Hiroyuki Kuwae, Waseda Univ. (Japan); Juro Oshima, Nissan Chemical Industries, Ltd. (Japan); Ryoichi Ishimatsu, Shuya Tashiro, Toshihiko Imato, Chihaya Adachi, Kyushu Univ. (Japan); Shuichi Shoji, Jun Mizuno, Waseda Univ. (Japan)

Liquid-organic light-emitting diodes (OLEDs), which have liquid light-emitting layers with liquid organic semiconductors (LOSs), have much attention for future organic electronics applications. LOSs have potential for recovery emission replacing the deteriorated emitters. Deep-blue light is essential for the development of liquid-OLED applications such as displays and light sources for medical treatment, however, liquid deep-blue light emission have hardly been reported because wide-bandgap liquid emitters are limited. Thus, in this study, we propose liquid deep-blue light emission with a novel wide-bandgap LOS host by means of the host-guest energy transfer.

1-Naphthaleneacetic acid 2-ethylhexyl ester (NLQ) (Nissan Chemical Industries, Ltd.), which is a naphthalene-derivative LOS, was applied as a liquid host material. 9,10-Diphenyl anthracene (DPA) (Tokyo Chemical Industry Co., Ltd.) was doped into the liquid host as the guest deep-blue emitter.

NLQ shows strong absorption at 280 nm or less, and the bandgap Eg of NLQ was estimated to be 4.1 eV. It is the first reports on the LOS with the bandgaps of greater than 4.0 eV, as far as we know. In addition, liquid electroluminescence (EL) emission of peak wavelength at 440 nm was successfully obtained from the doped system with wide-bandgap LOS at the applied voltage of 50 V. This result indicates that deep-blue emission was obtained by using the host-guest transfer, because NLQ has wider bandgap than DPA (Eg = 3.1 eV). From these results, we conclude that NLQ is expected to be a promising material for liquid-OLED applications.

10101-49, Session PWed

Polarization-resolved optical spectroscopy of crystalline perfluoropentacene on various substrates

Robin Carl Döring, Tobias Breuer, Gregor Witte, Philipps-Univ. Marburg (Germany); Sangam Chatterjee, Philipps-Univ. Marburg (Germany) and Institute of Experimental Physics I, Justus-Liebig-Univ. Giessen (Germany)

Perfluoropentacene (PFP) is the perfluorinated counterpart and hence n-type organic semiconductor to the prototypical p-type pentacene. It can be grown as highly crystalline thin films on various optically transparent substrates such as NaF, KCl, graphene and also graphene's opaque multilayer counterpart, highly ordered pyrolytic graphite (HOPG). While PFP forms the typical herringbone motif on both NaF and KCl, it shows a ϖ-stacking polymorph (PSP) on graphene and HOPG. Structural analyses show a ϖ-stacking distance of only 3.07 Å, promising far higher values for electron and hole mobility and therefore greatly improved vertical transport, a desirable feature in potential organic electronic applications. Here, we investigate the influence of the packing motif and hence of the intermolecular coupling on the optoelectronic properties. Making use of polarization resolved optical spectroscopy with high spatial resolution, we identify the corresponding exciton transition energies and correlate them

with the orientation of crystalline domains and the substrate. Unfortunately, due to the face-on growth of the molecules, the ϖ-stacking axis of the PSP polymorph is inaccessible under normal angle of incidence. Hence, we perform close to grazing incidence photomodulated reflection spectroscopy and compare the obtained results to those of the other polymorphs.

10101-50, Session PWed

Influences of device structures on the microstructure-correlated photovoltaic characteristics of organic solar cells

Fu-Chiao Wu, Cheng-Chi Yang, Po-Tsung Tseng, Wei-Yang Chou, Horng-Long Cheng, National Cheng Kung Univ. (Taiwan)

The photovoltaic characteristics of organic solar cells (OSCs) are correlated with the microstructural qualities of active layers (ALs). Many efforts have focused on improving the process conditions of ALs to attain effective microstructures in order to achieving high efficiency OSCs. In addition to AL process conditions, the properties of the layer under the AL also can influence the growth of the AL and result in different microstructural qualities. In this study, we adopted poly(3-hexylthiophene) (P3HT):(6,6)-phenyl C61-butyric acid methyl ester (PCBM) mixture as the AL, poly(3,4-ethylenedioxythiophene):poly (styrene sulfonate) (PEDOT:PSS) as the hole extraction layer, and branched polyethyleneimine (BPEI) as the electron extraction layer to prepare OSCs with different device structures, that is, normal type (PEDOT:PSS/P3HT:PCBM/BPEI) and inverted type (BPEI/P3HT:PCBM/PEDOT:PSS) structures. We found that the photovoltaic characteristics of this two kinds of devices were dissimilar although their layer components were the same. The inverted devices performed higher power conversion efficiency (PCE) than the normal devices. Various methods, including absorption spectroscopy, Raman spectroscopy, X-ray diffraction, and atomic force microscopy, were used to study the microstructures of the ALs of different devices. We observed that the P3HT crystallites grown on BPEI (inverted specimen) had larger dimension perpendicular to the substrate and smaller dimension parallel to the substrate, compared with those grown on PEDOT:PSS (normal specimen). This shape of P3HT crystallites in the inverted devices facilitated efficient charge transport to the electrodes and suppressed the occurrence of current leakage. As a result, the inverted devices generated improved short-circuit current, fill factor, and PCE.

10101-51, Session PWed

Controlling memory effects with a nano p-n heterojunction in n-type organic photo-memory transistors

Wei-Yang Chou, Sheng-Kuang Peng, Bo-Ren Lin, Yu-Fu Wang, Po-Kang Huang, Horng-Long Cheng, National Cheng Kung Univ. (Taiwan)

In the past years, organic photo-memory transistor (OPMT) devices have attracted considering attentions in organic electronics, because of their unique advantages, such as easily packed with integrated circuits, low-temperature manufacturing, and non-destructive reading out of digital signals. In OPMTs, the researches of n-type OPMT devices were relatively backward comparing with those of p-type devices. This may be attributed to the difficult synthesis and unstable structures under atmosphere environment for n-type semiconductors. In addition, minority carriers (i.e., holes) restrict the performances of n-type OPMTs. On the other hand, the p-type pentacene is usually used as a standard organic semiconductor for being an active layer, owing to its superior hole transport property between molecules. Therefore, in order to enhance the amount of holes, a very thin p-type pentacene film was deposited on the n-type semiconductor dioctyl perylene tetracarboxylic diimide (PTCDI-C13H27) to improve the memory window of OPMT devices. This pentacene layer was discontinuous formed on the PI/PTCDI observed atomic force and transmission electron microscopes. The in-plane (horizontal to the substrate) and out-of-plane (vertical to the substrate) crystal structures of pentacene films were analyzed by grazing angle x-ray diffraction (GIXRD). The GIXRD results demonstrate that the pentacene crystals are trending to three dimension growth on PTCDI-C13H27 monolayer below 5 nm thickness, and then transfer to layer-by-layer growth model when the thickness of pentacene layer is above 5 nm. This discontinuous pn-heterojunction has advantage of reduction of charge recombination for injection electrons in top contact geometry OPMTs.

Conference 10102: Ultrafast Phenomena and Nanophotonics XXI

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10102-1, Session 1

Active plasmonic photodetectors *(Invited Paper)*

Uriel Levy, Meir Grajower, Boris Desiatov, Noa Mazurski, Joseph Shappir, The Hebrew Univ. of Jerusalem (Israel); Jacob B. Khurgin, Johns Hopkins Univ. (United States)

In this talk we discuss our nnaoscale photodetectors for the near IR and the mid IR. Most of the devices are based on the process of internal photo emission from metal to silicon in Schottky type contacts. Efficiency limitations and approaches for improving quantum efficiency will be discussed.

10102-2, Session 1

Optical slot antenna and its application *(Invited Paper)*

Yeonsang Park, Jineun Kim, Young-Geun Roh, Samsung Advanced Institute of Technology (Korea, Republic of); Q-Han Park, Korea University (Korea, Republic of)

Here we present an optical slot nanoantenna and its applications. We fabricate a metal slot on the infinite metal film. The slot – inverted structure of a rod – interacts with electromagnetic waves in optical frequency range and shows magenetic dipole radiation experimentally and theoretically. Resonances and coupled polarizations are determined by the slot length and the slot-length direction. The feed tilted 45 degrees to excite selectively apart from other reflector and director slots. The directional radiation is observed from two slot antenna structures (a feed and a reflector) and the Front-to-Back(FB) ratio of an antenna with a reflector and three directors increases up to 5.

For the nanoantenna applications, we integrate a metal-insulator-metal (MIM) plasmonic waveguide to the slot antenna. Plamonic mode on MIM wave guide couples into the antenna feed that showing the dipole radiation pattern. The coupling efficiency of the integrated nanoantenna is calculated approximately 19% using finite-difference time-domain (FDTD) simulation. By adding an auxiliary groove structure along with the slot antenna, the radiation pattern shows the angular dependence where the structure determined. The demonstrated optical slot antenna integrated with a plasmonic waveguide can be used as a "plasmonic via" in plasmonic nanocircuits.

10102-3, Session 1

Electrically-driven optical antennas enabled by mesoscopic contacts *(Invited Paper)*

Alexander V. Uskov, P.N. Lebedev Physical Institute (Russian Federation) and ITMO Univ. (Russian Federation); Jacob B. Khurgin, Johns Hopkins Univ. (United States); Alexandre Bouhelier, Lab. Interdisciplinaire Carnot de Bourgogne (France) and Ctr. National de la Recherche Scientifique (France) and Univ. Bourgogne Franche-Comté (France); Mickael Buret, Lab. Interdisciplinaire Carnot de Bourgogne (France) and Ctr. National de la Recherche Scientifique (France) and Univ. de Bourgogne Franche-Comté (France); Igor V. Smetanin, Igor E. Protsenko, P.N. Lebedev Physical Institute (Russian Federation)

Electrically driven optical antennas are attracting much attention, in particular, due to necessity to develop integrated electrical source of surface plasmons for future plasmonic nanocircuitries. By default, this term denotes a metal nanostructure, in which electromagnetic oscillations at optical frequencies are excited by electrons, tunneling between metallic parts of the structure when a bias voltage is applied between them.

Instead of relying on an inefficient inelastic light emission in a tunnel gap, we are suggesting to use ballistic nanoconstrictions as the feed element of an optical antennas in order to excite electromagnetic plasmonic modes. Similarly to tunneling structures, the voltage applied at the constriction falls over the contact of nanoscale length. Electron passing through the contact ballistically can gain the energy provided by the bias ~1eV and exchange it into an mode of the optical antenna. We discussed the underlying mechanisms responsible for the optical emission, and show that with nanoscale contact, one can reach quantum efficiency orders of magnitude larger than with standard tunneling structures.

The research leading to these results has received funding from the Government of the Russian Federation (Grant 074-U01) through ITMO Visiting Professorship program, the European Research Council under the European Community' s Seventh Framework Program FP7/20072013 Grant Agreement no. 306772, and Program MAZON of the French Embassy in the Russia.

10102-4, Session 1

Thermochromic modulation of surface plasmon polaritons in vanadium dioxide nanocomposites

Thorben Jostmeier, Technische Univ. Dortmund (Germany); Moritz Mangold, Johannes Zimmer, Helmut Karl, Hubert J. Krenner, Univ. Augsburg (Germany); Claudia Ruppert, Markus Betz, Technische Univ. Dortmund (Germany)

We propose and implement a new concept for thermochromic plasmonic elements. It is based on vanadium dioxide (VO2) nanocrystals located in the near field of surface plasmon polaritons supported by an otherwise unstructured gold thin film. When the VO2 undergoes the metal-insulator phase transition, the coupling conditions for conversion of light into propagating surface plasmon polaritons change markedly. In particular, we realize thermochromic plasmonic grating couplers with substantial switching contrast as well as tunable plasmonic couplers in a Kretschmann configuration. The use of VO2 nanocrystals permits highly repetitive switching and room temperature operation. Simulations based on the actual dielectric function of our VO2 nanocrystals agree well with the experiment.

10102-5, Session 2

Nanosystems in ultrafast and superstrong fields: attosecond phenomena *(Keynote Presentation)*

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

We present our latest results for a new class of phenomena in condensed matter nanooptics when a strong optical field ?1-3 V/? changes a solid within optical cycle [1-8]. Such a pulse drives ampere-scale currents in dielectrics and adiabatically controls their properties, including optical absorption and reflection, extreme UV absorption, and generation of high harmonics [9] in a non-perturbative manner on a 100-as temporal scale. Applied to a metal, such a pulse causes an instantaneous and, potentially, reversible change from the metallic to semimetallic properties. We will also discuss our latest theoretical results on graphene that in a strong ultrashort

pulse field exhibits unique behavior [10-12]. New phenomena are predicted for buckled two-dimensional solids, silicene and germanene [13]. These are fastest phenomena in optics unfolding within half period of light. They offer potential for petahertz-bandwidth signal processing, generation of high harmonics on a nanometer spatial scale, etc.

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10102-6, Session 2

Dynamical nonlinear interactions of solids with strong terahertz pulses *(Invited Paper)*

Hideki Hirori, Kyoto Univ. (Japan)

The laser dressing of electronic eigenstates leads to important quantum optical phenomena, such as Rabi splitting, optical Stark effect, and electromagnetically induced transparency, for the applications of ultrafast optical switching, slowed and stored light, and quantum information processing. Excitons are strongly correlated pairs of electrons and holes and dominate the absorption spectrum of semiconductor near bandgap energy. The intraexcitonic transition energy lies in the terahertz (THz) frequency range with large dipole moments, which making them fascinating system not only for studying the fundamentals of nonlinear optics also exploiting THz excitonic interactions in optical communication devices. However, so far, the study of the effect of excitonic dressed states on the optical field is limited to the usage for a single optical frequency as a probe and the driving-cycle-averaged optical experiments. Here, we probe the transient absorption changes of near-infrared (NIR) pulse in a GaAs quantum well under the presence of a multi-cycle THz wave. By changing the delay between the NIR probe and the THz wave the absorption strengths are modulated on the sub-cycle THz timescale, and the frequency analysis shows the formation of THz-induced dressed states of excitons. Besides the novel concept for sub-cycle control of optical properties, our findings reveal the importance of accounting for interference effects of THz-induced nonlinear susceptibilities in the interpretation of THz pump–optical probe experiments.

10102-7, Session 2

Ultrafast nonlinear and strong-field phenomena in silicon-loaded nanoplasmonic waveguides *(Invited Paper)*

Matthew S. Sederberg, Univ. of Alberta (Canada); Abdulhakem Y. Elezzabi, Univ of Alberta (Canada)

We generate femtosecond pulses at ?=517nm in subwavelength silicon-based nanoplasmonic waveguides via third-harmonic conversion of ?=1550nm pulses with an efficiency,?=2.3?10^-5. This marks the highest third-harmonic conversion efficiency in a silicon-based or nanoplasmonic structure and the smallest silicon waveguide structure demonstrated to date. The high conversion efficiency is attributed to tight electric field confinement and strong light-matter coupling arising from surface plasmon modes in the nanoplasmonic waveguide, enabling efficient nonlinear optical mixing. The non-resonant waveguide geometry enables the entire ?=1550nm pulse spectrum to be converted to its third-harmonic, which may be easily extended to the entire visible spectrum.

Subsequently, we investigate ponderomotive electron acceleration in a silicon-loaded nanoplasmonic waveguide. Photogenerated free-carriers are accelerated by the tightly confined nanoplasmonic fields and reach energies exceeding the threshold for impact ionization. Exponential growth of white light emission confirms the presence of a plasmonic-field-driven electron avalanche. Electron sweeping dynamics are visualized using pump-probe measurements and a sweeping time of 1.98±0.40ps is measured.

We envisage that third-harmonic generation in silicon-based nanoplasmonic waveguides could provide a platform for integrated, broadband visible light sources and entangled triplet photons on future hybrid electronic-silicon photonic chips. The sweeping electron density dynamics mark a new means to achieve all-optical modulation in a nanoplasmonic device, with the potential to achieve signal modulation at bandwidths up to 500GHz. The compatibility of these devices with modern electronics circuitry and the silicon photonics platform demonstrate the potential for monolithic integration of nanoscale devices from each of these platforms.

10102-8, Session 2

Ultrastrong light-matter coupling at 300 GHz with few (<80) electrons

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Strong light-matter coupling lies at the heart of quantum optics and recently has been successfully explored also in the GHz and THz range. New, intriguing quantum optical phenomena have been predicted in the ultrastrong coupling regime, when the coupling strength Omega becomes comparable to the unperturbed frequency of the system omega_c. We recently proposed a new experimental platform where the physics of the ultrastrong coupling can be investigated at GHz-THz frequencies. We couple the inter-Landau level transition of an high-mobility 2 dimensional electron gas (2DEG) to the subwavelength photonic mode of an LC meta-atom. Our system benefits from the collective enhancement of the light-matter coupling which comes from the scaling of the coupling constant Omega

with the square root of the number of electrons in the last Landau level. In our previous experiments and in literature this number varies from 10000-1000 electrons per resonator.

Here we present ultrastrong coupling between a high-mobility 2DEG (mu=2.3X 10^6 cm^2/Vs) and an extremely subwavelength hybrid-LC resonator ensemble (11 resonators) with an highly reduced effective mode volume V_eff=4 x 10^-19 m^3=4 x 10^(-10) lambda^3 at a frequency of 300 GHz. The number of optically active electrons is given by the flux quantum multiplied by the effective resonator area and is proportional to the magnetic field. At the anticrossing field of B=0.73 T we measure less than 80 electrons ultrastrongly coupled to the resonator with a normalized coupling ratio Omega/omega_c=0.35. This experiment paves the way towards the study of ultrastrong coupling physics in the regime of quantum non-linearities.

10102-9, Session 3

Ultrafast magnetization dynamics probed with XUV pulses from HHG via magneto-optics and spin-resolved ARPES *(Invited Paper)*

Stefan Mathias, Georg-August-Univ. Göttingen (Germany)

Ultrashort extreme-ultraviolet pulses generated by high-harmonic generation (HHG) provide a powerful tool for novel experiments in the area of ultrafast materials science. The short-wavelength nature of these sources allows access to the electronic, magnetic, structural, and chemical properties of solids.

Here, we use HHG-based magneto-optical and photoemission experiments to probe ultrafast magnetic processes with ultrahigh time-resolution and element-specificity. Using element-specific HHG magneto-optical techniques, we demonstrate the importance of photo-induced superdiffusive spin currents in magnetic multilayer stacks. With the help of a HHG time-, spin-, and angle-resolved photoemission (spin-resolved trARPES), we map the spin-dependent band structure response of a thin Co film during ultrafast demagnetization. This allows us unprecedented access to the dynamically evolving electronic band structure to observe distinctly different processes at work. At energies near the Fermi-level, the spin dynamics are predominantly driven by a redistribution of spin-polarized carriers. At higher binding energies >1 eV, quenching of the spin polarization exhibits transient band dynamics that can be unambiguously traced back to rapid band mirroring of the electronic states. Our results indicate that spin currents are playing a dominant role in the demagnetization process in this material, and elucidate why past work that probed different parts of the electronic band structure yielded seemingly contradictory results.

10102-10, Session 3

Three-stage decoherence dynamics of an electron spin qubit in an optically active quantum dot

Alexander Bechtold, Technische Univ. München (Germany); Tobias Simmet, Per-Lennart Ardelt, Dominik Rauch, Walter Schottky Institut (Germany); Fuxiang Li, Los Alamos National Lab. (United States); Nikolai A. Sinitsyn, Los Alamos National Lab. (United States); Kai Müller, Jonathan J. Finley, Walter Schottky Institut (Germany)

Using solid-state spin qubits for quantum information processing requires a detailed understanding of the decoherence mechanisms. For electron spins in quantum dots (QDs), considerable progress has been achieved in strong external magnetic fields; however, decoherence at very low magnetic fields remains puzzling when the magnitude of the Zeeman energy becomes comparable with intrinsic couplings. Phenomenological models of decoherence currently recognize two basic types of spin relaxation; fast ensemble dephasing due to the coherent precession of spin qubits around nearly static but randomly distributed hyperfine fields (?2ns) and a much slower process (>1?s) of irreversible monotonic relaxation of the spin qubit polarization due to nuclear spin co-flips with the central spin or due to other complex many-body interaction effects [1]. Here, we demonstrate experimentally and theoretically that not only two but three distinct stages of decoherence can be identified in the relaxation of a QD electron spin qubit. Measurements and simulations of the spin projection without an external field clearly reveal an additional decoherence stage at intermediate timescales [2]. The additional stage corresponds to the effect of coherent dephasing processes that occur in the nuclear spin bath itself induced by quadrupolar coupling of nuclear spins to strain driven electric field gradients, leading to a relatively fast but incomplete non-monotonic relaxation of the central spin polarization at intermediate (?750ns) timescales.

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10102-11, Session 3

Electron-nuclear coherent spin oscillations probed by the spin-dependent recombination in band-to-band photoluminescence

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Electron and nuclear spins of well-isolated point defects in semiconductors are excellent candidate for understanding fundamental spin-coupling mechanisms or to model quantum information processing. Optically or electrically detected magnetic resonance techniques are consistently employed for manipulating and probing the defect spins through the hyperfine interaction, or again to identify the defect chemical nature and related spin dependent recombination pathways. Here we demonstrate a detection scheme of the hyperfine interaction features and defect configuration of gallium interstitial paramagnetic defects in dilute nitride GaAsN based on the measurement of the coherent electron-nucleus spin oscillations through the band-to-band photoluminescence. The implementation of a pump and probe photoluminescence experiment leads to the measurement, in the temporal domain, of the hyperfine constant by directly tracing the hyperfine interaction dynamical behavior. The hyperfine constants, defect configuration and the relative abundance of the nuclei involved can be determined without the need of electron spin resonance techniques and in the absence of any magnetic field. Information on the nuclear and electron spin relaxation damping parameters can also be estimated from the oscillations damping and the long delay behavior.

10102-12, Session 3

Polariton formalism for semiconductor double microcavities

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The optical spin Hall effect (OSHE) is a linear optical effect of exciton polaritons in semiconductor microcavities. It originates from the polaritonic spin-orbit coupling, and can lead to observable spin/polarization textures in the near and far field under appropriate non-textured excitation conditions. A convenient description is based on a pseudo-spin model, where the pseudo-spin is given by the Stokes parameter S1, S2 and S3 of the polariton field. The formation of the OSHE texture can be described by an effective magnetic field that is caused by the splitting of the transverse-magnetic and transverse-electric (TE-TM) polariton modes. In the linear or low density regime, it is limited in the 2-dimensional S1-S2 plane of the 3-dimensional pseudospin space. In this work, we show theoretically and experimentally that the pseudo-spin texture can be controlled all-optically in a specific double-microcavity design. In theory, the effective magnetic field can be moved out from the 2-dimensional S1-S2 plane by increasing the incident light intensity. This leads to a rotation of the pseudo-spin pattern. We established a one-to-one correspondence between the incident light intensity and the degree of rotation of the far-field pattern by solving both the simplified pseudo-spin model and the more general double-cavity spinor-polariton Gross-Pitaevskii equations. Our numerical results are in good agreements with our experimental data, indicating that we have indeed achieved a well-controlled rotation of the OSHE texture. Our scheme provides a simple and robust control mechanism for future spinoptronic devices utilizing OSHE.

10102-13, Session 3

Enhanced spin-polarization lifetimes in a two-dimensional electron gas in a gate-controlled GaAs quantum well

Sergiu Anghel, Technische Univ. Dortmund (Germany); Akshay Singh, The Univ. of Texas at Austin (United States); Felix Passmann, Technische Univ Dortmund (Germany); Hikaru Iwata, Tohoku Univ. (Japan); John N. Moore, Tohoku Unive. (Japan); Go Yusa, Tohoku Univ. (Japan); Xiaoqin Li, The Univ. of Texas at Austin (United States); Markus Betz, Technische Univ. Dortmund (Germany)

Exciton, trion, and electron spin dynamics in a 20-nm-wide modulation-doped GaAs single quantum well are investigated using resonant ultrafast two-color Kerr rotation spectroscopy. Excitons and trions are selectively detected by resonant probe pulses while their relative spectral weight is controlled by adjusting the gate voltage which tunes the carrier density. Tuning the carrier density markedly influences the spin decay time of the two-dimensional electron gas. The spin decay time can be enhanced by a factor of 3 at an intermediate carrier concentration in the quantum well where excitons and trions coexist in the system. In addition, we explore the capability to tune the g factor of the electron gas via the carrier density.

10102-14, Session 3

Optically-probing spin qubit coherence without coherent control

Kai Müller, Alexander Bechtold, Walter Schottky Institut (Germany); Fuxiang Li, Los Alamos National Lab. (United States); Tobias Simmet, Walter Schottky Institut (Germany); Nikolai A. Sinitsyn, Los Alamos National Lab. (United States); Jonathan J. Finley, Walter Schottky Institut (Germany)

We demonstrate an entirely new method to probe quantum measurement phenomena in semiconductor quantum dot (QD) spin qubits [1]. In addition to providing direct evidence for the quantum nature of solid state qubits, we show that our method has practical importance since it provides a completely alternative route for measuring ensemble and quantum dephasing times, T2* and T2, using only repeated projective measurements and without the need for coherent spin control.

Our approach is based on measuring time-correlators of a spin qubit in an optically active QD beyond the second order. We utilize a quantum dot spin-storage structure to initialize a single electron spin in a quantum dot subject to a magnetic field applied in Voigt geometry through tunnel ionization and perform repeated projective measurements of the spin at times t1 and t2. This measurement is repeated, corresponding to ensemble averaging, and the resulting third-order time correlations reveals rich physics: For times t1 or t2 < T2* Larmor precession is observed which reveals the ensemble dephasing time T2*. Importantly, even though the time-correlators were obtained through averaging many measurements for times t1 and t2 > T2* oscillations are observed that decay with the dephasing time T2 and allow its determination even without the need for coherent spin control. Finally, combining the third-order time correlator with the second-order time correlator allows to demonstrate a violation of Leggett-Garg type inequalities for certain times providing clear evidence for the quantum nature of the quantum dot spin.

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10102-15, Session 4

Modelling and physical interpretation of time-delay differences observed in attosecond-time-resolved photoemission from WSe2 and BiTeCl surfaces *(Invited Paper)*

Walter Pfeiffer, Univ. Bielefeld (Germany)

The availability of single attosecond (as) XUV pulses allows investigating ultrafast electron dynamics on the as time scale by recording slight temporal shifts of the photoelectron streaking in a simultaneously present strong IR field. The physical origin of the observed small delays is not yet understood and controversial theoretical models coexist demonstrating our still limited understanding of the fundamentals of the photoemission process. Here we report our progress to model and interpret photoemission delays measured using as-time-resolved photoemission from the layered crystals WSe2 and the non-centrosymmetric BiTeCl. Quantum mechanical modelling on the single particle level and classical trajectory calculations yield no satisfactory explanation of the observed relative delays between photoemission events from different initial states. Local atomic effects and many body corrections occurring inside the atom from which the electron is emitted yield significant corrections to the total photoemission delay and improve the match between experimental observation and theoretical prediction. This sheds new light on the fundamental mechanism involved in the photoemission process and shows that a refined model of photoemission that accounts for these local effets is needed.

10102-16, Session 4

Cavity nonlinear optics with monolayer materials *(Invited Paper)*

Arka Majumdar, Univ. of Washington (United States)

Realizing low-power (few-photon) nonlinear optics in a scalable way is important for both fundamental scientific studies to build strongly correlated “quantum fluids of light” and technological applications, including optical information processing. In recent years, such single photon nonlinearity has been reported using cavity coupled single emitters, including quantum dots, and atoms. However, the macroscopic size of atomic physics cavities, and stochastic spatial and spectral nature of quantum dots pose a serious problem for the scalability. In my talk, I will introduce a new platform with cavity coupled to patterned monolayer materials to accomplish this goal. I will present theoretical analysis of a coupled system of cavity-transition metal dichalcogenides and provide some preliminary experimental data on nonlinear optics with cavity and monolayer materials.

10102-17, Session 4

Ultrafast extreme-ultraviolet ARPES studies of electronic dynamics in two-dimensional materials *(Invited Paper)*

Jan Heye Buss, Julian Maklar, Hyejin Ryu, Frederic Joucken, He Wang, Yiming Xu, Alessandra Lanzara, Sung-Kwan Mo, Robert A. Kaindl, Lawrence Berkeley National Lab. (United States)

Two-dimensional materials such as graphene and transition-metal dichalcogenides (TMDC) exhibit intriguing physical properties, such as massless fermions, large spin-orbit splitting, or strongly-bound excitons. This motivates experiments to resolve and control their non-equilibrium dynamics, both to clarify the underlying microscopic interactions and to enable future opto-electronic applications that exploit ultrafast dynamics and optically-addressable spin- and valley degrees of freedom. Essential insight into the electronic momentum-space dynamics can be obtained directly via time- and angle-resolved photoemission spectroscopy (trARPES). Here, we present the development and application of a powerful high-repetition rate (50-kHz) trARPES setup for sensitive studies of materials dynamics, based on a novel table-top source of bright and narrowband extreme-UV harmonics around 22.3 eV. In bulk MoSe2, intervalley-scattering is directly observed in momentum space after resonant excitation of excitons, associated with a rapid increase of electron density at the K-Point and subsequent transfer towards the conduction band minimum on a sub?100 fs time scale. We will discuss this and other applications to studies of non-equilibrium carrier dynamics across the full Brillouin zone of both bulk and monolayer quantum materials.

10102-18, Session 4

Ultrafast carrier dynamics of epitaxial silicene

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The recent integration of silicene in field-effect transistors (FET) opened new challenges in the comprehension of the chemical and physical properties of this elusive two-dimensional allotropic form of silicon. Intense efforts have been devoted to the study of the epitaxial Silicene/Ag(111) system in order to elucidate the presence of Dirac fermion in analogy with graphene; strong hybridization effects in silicene superstructures on silver have been invoked as responsible for the disruption of ϖ and ϖ* bands. In this framework, the measured ambipolar effect in silicene-based FET characterized by a relatively high mobility, points out to a complex physics at the silicene-silver interface, demanding for a deeper comprehension. One way to tackle this issue is to study the stationary and time-dependent dielectric response of silicene/Ag(111) therein including the optical absorption and the transient reflectance spectroscopy. In the former case, the silicene/Ag(111) spectra, which turn out to be strongly non-additive, are analyzed in the framework of theoretical density-functional based calculations allowing us to identify different contributions. Electronic transitions involving silver states are found to provide a huge contribution to the optical absorption of silicene, compatible with a strong Si-Ag hybridization. The results point to a dimensionality-driven peculiar dielectric response of the two-dimensional-silicon/Ag(111) interface, which is confirmed by means of Transient-Reflectance spectroscopy spectroscopy. This analysis shows a metallic-like carrier dynamics, hence providing an optical demonstration of the strong hybridization arising in silicene/Ag(111) systems. Our findings can have a strong impact in the case of other supported elemental 2D materials, such as supported X-enes.

10102-19, Session 4

Long-lived quantum emitters in hBN-WSe2 van-der-Waals heterostructures

Jakob Wierzbowski, Christian Straubinger, Florian Sigger, Julian Klein, Michael Kaniber, Kai Müller, Jonathan J. Finley, Walter Schottky Institut (Germany)

We present detailed investigations of the optical properties of single photon emitters forming in 2D hBN-WSe2 van-der-Waals (vdW) heterostructures demonstrating the potential of hBN as a high quality environment for vdW heterostructure devices.

The samples investigated are monolayer WSe2 crystals that are fully encapsulated within multi-layer hBN crystals using viscoelastic stamping techniques [1]. We observe a reduction of the bulk WSe2 exciton linewidth to ~4 meV for both X0 and X- transitions, a reduction of 50% compared to WSe2 placed directly on Si/SiO2 substrates, arising from suppressed non-radiative decay channels due to the hBN encapsulation [2].

For low excitation power densities (P < 2 W/cm?), the emission spectrum is dominated by localized sharp (FWHM < 1 meV) emission lines redshifted by ~100meV from the exciton photoluminescence. Second-order photon correlation measurements reveal clear photon anti-bunching behaviour of the localized emitters. Time-resolved photoluminescence measurements reveal a mono-exponential lifetime of ~25 ns, 10-times longer than reported in recent works [3-4]. Polarization-resolved experiments show a significant fine structure splitting of single emission lines ranging from 0.5 meV to 1 meV.

Finally, we present measurements performed with hBN-WSe2 heterostructures prepared on a ZrO2 solid immersion lens (SIL). Hereby, we enhance the spatial resolution by a factor of ~5x and determine an upper bound of the spatial extent of the localized emitters to be ~250 nm.

Our results demonstrate the potential of employing hBN as a high quality substrate for optimized optical properties of delocalized and localized emission of excitons in WSe2.

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10102-20, Session 5

Electron interactions and vibrations in metallic clusters *(Invited Paper)*

Fabrice Vallee, Aurélien Crut, Paolo Maioli, Tatiana Stoll, Natalia Del Fatti, Univ. Claude Bernard Lyon 1 (France)

Reduction of the size of a material to the nanometric range drastically modifies many of its physical and chemical properties. For metal nano-objects with size down to a few nanometers, these modifications mainly originate from classical effects, while for smaller sizes below about 2 nm (less than about 250 atoms), quantization plays an important role. Though the impact of quantization on static properties (ionization threshold, melting temperature, optical absorption, …) of free clusters has been extensively

investigated, the induced changes of the electronic interactions and of their vibrational response have been much less studied.

Using high-sensitivity ultrafast pump-probe spectroscopy, we investigated the electron kinetics and vibrations of metal nanoparticles formed by few hundred to few atoms. The relaxation process of photoexcited nonequilibrium electron was followed in the time-domain, yielding information on the electron-electron and electron-vibration energy exchange processes. Investigations have been performed both in surfactant-free glass-embedded silver clusters to limit surface effects, and in chemically synthesized gold cluster stabilized with thiols. The efficiency of the electronic interactions is observed to increase with size reduction down to about 2 nm, consistently with previous results in larger size particles. However, it is shown to decrease for smaller sizes, an effect ascribed to quantization of the electronic states. Size dependence of the acoustics vibrational response of silver and gold clusters in this size range will also be discussed in the context of transition from an elastic body (macroscopic elastic model) to a molecular type of description of the vibrational modes of nano-objects.

10102-21, Session 5

Thermo-plasmonics: playing with temperature at the nanoscale *(Invited Paper)*

Alessandro Alabastri, Rice Univ. (United States); Mario Malerba, Eugenio Calandrini, Andrea Toma, Istituto Italiano di Tecnologia (Italy); Remo Proietti Zaccaria, Istituto Italiano di Tecnologia (Italy) and Chinese Academy of Sciences (China)

The electro-magnetic field generated within and around dissipative nano-structures upon light radiation is intimately associated to the formation of localized heat sources. In turn, this phenomenon determines localized temperature variations, effect which can be exploited for applications such as photocatalysis [1], nanochemistry [2] or sensor devices [3].

Here we show how the geometrical characteristics of plasmonic nano-structures can indeed be used to modulate the temperature response. The idea is that when metallic structures interact with an electromagnetic field they heat up due to Joule effect. The corresponding temperature variation modifies the optical response of the structure [4,5] and thus its heating process. The key finding is that, depending on the structures geometry, absorption efficiency can either increase or decrease with temperature. Since absorption relates to the thermal energy dissipation and thus to temperature increase, the mechanism leads to positive or negative loops. Consequently, not only an error would be made by neglecting the role of temperature, but it would be not even possible to know, a priori, if the error is towards higher or lower absorption values.

Our model can be utilized to study opto-thermal phenomena when high temperature or high intensity sources are employed.

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10102-22, Session 5

Femtosecond relaxation dynamics of Tamm plasmon-polaritons

Vladimir O. Bessonov, Boris I. Afinogenov, Anna Popkova, Andrey A. Fedyanin, M.V. Lomonosov Moscow SU (Russian Federation)

Tamm plasmon-polariton (TPP) is an optical analogue of Tamm state and appears as spatial localization of the electromagnetic field near the boundary of one-dimensional photonic crystal (PC) (distributed Bragg reflector) and a metal film. TPP can be detected experimentally as a narrow resonance in the reflectance or transmittance spectrum of a PC/metal structure. Contrary to surface plasmon-polariton TPP occurs at any angles of incident light for both TE and TM polarizations, and it excitation does not require sophisticated optical schemes (such as Kretchmann scheme). The peculiarities of TPP optical properties led to considerable interest to the design, fabrication and study of TPP-supported structures in the past several years.

In present work, the ultrafast relaxation dynamics of TPP excited in the PC/metal structures is measured using intensity cross-correlation scheme. The TPP lifetime is obtained for different polarizations and incident angles of light, and compared with one obtained from numerical calculations. A femtosecond pulse reflected from such a structure is found to be significantly distorted if its spectrum overlaps with the TPP resonance. The TPP lifetime possesses strong polarization and angular dependence and is shown to vary from 20 fs for p-polarized light to 40 fs for s-polarized light at a 45? angle of incidence. The reported lifetime of TPP is several times smaller than the previously reported lifetime of surface plasmons. Short lifetime and sharpness of resonance make TPP a good candidate for use in all-optical switches and modulators.

10102-23, Session 5

High-speed polarization modulation in a hybrid ridge-plasmonic waveguide

Curtis J. Firby, Univ. of Alberta (Canada); PoHan Chang, Amr S. Helmy, Univ. of Toronto (Canada); Abdulhakem Y. Elezzabi, Univ. of Alberta (Canada)

We present the design and theoretical characterization of a magnetoplasmonic Faraday rotator for active polarization control in integrated plasmonics. By incorporating bismuth-substituted yttrium iron garnet (Bi:YIG) into a unique hybrid ridge-plasmonic waveguide structure, we effectively overcome the phase matching limitations between photonic TE and plasmonic TM modes, and hence attain efficient Faraday rotation within a plasmonic device. The device provides 99.4% polarization conversion within a length of 830μm, while the two modes exhibit propagation lengths in excess of 1mm. This versatile optical building block can be operated with either a TE or TM input, making it ideal for polarization switching and polarization division multiplexing. Additionally, a buried Ag transmission line under the waveguide facilitates high-speed active polarization modulation by generating transient magnetic fields and modulating the Bi:YIG magnetization. We show that with these transient fields and an external static biasing field, one can operate the device in either a pulsed-input pulsed-output mode, to produce a polarization switch, or a pulsed-input continuous-output mode, to produce a polarization oscillator. Such a device is shown to be capable of polarization modulation of 10GHz, and will be vital in realizing plasmonic circuits employing polarization diversity.

10102-24, Session 6

A Microscopic Approach to Ultrafast Near Band Gap Photocurrents in Bulk Semiconductors *(Invited Paper)*

Reinold Podzimski, Univ. Paderborn (Germany); Huynh Thanh Duc, Vietnam Academy of Science and Technology (Viet Nam); Torsten Meier, Univ. Paderborn (Germany)

In unbiased non-centrosymmetric solid state systems it is possible to excite electronic currents on ultrafast femtosecond time scales using optical laser pulses. Here, we present and analyze a microscopic theory that is capable

of describing the generation of injection, shift, and rectification currents in GaAs and GaAs based quantum wells. The band structure and the wave functions are computed via 14x14 band k.p theory. This approach includes the anisotropy of the band structure and the spin-orbit interaction. Using the k.p band structure and wave functions, the optical matrix elements are computed and inserted into the semiconductor Bloch equations, i.e., the equations of motion of the optically induced polarizations and carrier occupations. The current transients are obtained by numerical solutions of the semiconductor Bloch equations. It is shown that the often employed perturbative second-order approach breaks down for peak fields larger than about 10 kV/cm and that non-perturbative effects may lead to a reduction of the peak values of the currents and to temporal oscillations originating from Rabi flopping. Furthermore, we find a complex oscillatory photon energy dependence of the magnitudes of the shift and rectification currents. Our simulations demonstrate that this dependence is mainly due to band mixing. Comparing to experiments performed on [110]-oriented GaAs quantum wells we find a good agreement which confirms our theoretical approach.

10102-25, Session 6

Momentum space view of the ultrafast dynamics of surface photocurrents on topological insulators *(Invited Paper)*

Kenta Kuroda, Institute for Solid State Physics, The Univ. of Tokyo (Japan); Johannes Reimann, Jens Güdde, Ulrich Höfer, Philipps-Univ. Marburg (Germany)

The Dirac-cone surface states of 3D topological insulators are characterized by a chiral spin texture in k-space with the electron spin locked to its parallel momentum. We demonstrate by means of time- and angle-resolved two-photon photoemission (2PPE) that pulsed laser excitation of such a topological surface state (TSS) in Sb2Te3 offers the possibility to create and control spin-polarized electrical surface currents on ultrafast timescales [1].

We employ mid-infrared (MIR) pulses with photon energies below the bulk band gap (?? = 0.2 - 0.4 eV) in order to directly excite electrons from the occupied into the unoccupied part of the TSS. With this pump scheme across the Dirac point, we are able to create a pronounced asymmetry of the transient TSS population in k-space which corresponds to a spin-polarized photocurrent in real space. Time-delayed photoemission out of the TSS allows for detailed investigations of the microscopic scattering processes leading to the decay of the surface currents. The elastic scattering times of 2.5 ps deduced for Sb2Te3 corresponds to a mean-fee path of 0.6 um in real space. These values exceed those of electrons on metal surfaces by two orders of magnitude. The results provide clear experimental evidence that the TSS electrons are effectively protected from back scattering by phonons and non-magnetic impurities.

[1] K. Kuroda, J. Reimann, J. Güdde, and U. Höfer , PRL 116, 076801 (2016)

10102-26, Session 6

Selective resolution of photocurrent generating pathways in transition metal dichalcogenides by ultrafast microscopy *(Invited Paper)*

Matthew W. Graham, Oregon State Univ. (United States)

Presently, there exists no reliable in-situ time-resolved method that selectively isolates both the recombination and escape times relevant to photocurrent generation in the ultrafast regime. Transport based measurements lack the required time resolution, while purely optical measurement give a convoluted weighted-average of all electronic dynamics, offering no selectivity for photocurrent generating pathways. Recently, the ultrafast photocurrent (U-PC) autocorrelation method has successfully measured the rate limiting electronic relaxation processes in materials such as graphene, carbon nanotubes, and transition metal dichalcogenide (TMD) materials. Here, we unambiguously derive and experimentally confirm a generic U-PC response function by simultaneously resolving the transient absorption (TA) and U-PC response for highly-efficient (48% IQE at 0 bias) WSe2 devices and twisted bilayer graphene. Surprisingly, both optical TA and electrical U-PC responses give the same E-field-dependent electronic escape and recombination rates. These rates further accurately quantify a material's intrinsic PC generation efficiency. We demonstrate that the chirality of the incident light impacts the U-PC kinetics, suggesting such measurements directly access the ultrafast dynamics need to complex electronic physics such as the valley-Hall effect. By combining E-field dependent ultrafast photocurrent with transient absorption microscopy, we have selectively imaged the dominant kinetic bottlenecks that inhibit photocurrent production in devices made from stacked few-layer TMD materials. This provides a new methodology to intelligently select materials that intrinsically avoid recombination bottlenecks and maximize photocurrent yield.

10102-27, Session 6

Lowering the barrier for photoemission in eCarbon/Au bilayer driven by a plasmonic field

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We demonstrate that the potential barrier for photoemission in an eCarbon/Au bilayer can be lowered such that there is an enhanced photoelectron yield at a given intensity. A Ti:sapphire laser with a central wavelength of 780nm is employed to excite surface plasmon (SP) waves in the bilayer using the Kretschmann geometry. The bilayer consists of a thin, 10nm, layer of electron beam deposited carbon (eCarbon or e-C) under a 45nm Au layer. At high laser intensities, the electron yield from the bilayer is 60% higher than that of an Au film by itself. The origin of the enhanced emission can be ascertained by determining the order of the emission process. For an Au film by itself, the emission order is 2.88, indicating a three-photon process is dominating a two-photon process. Notably, the emission order for the e-C/Au bilayer lowers to 2.44, indicating that a two-photon process is now dominating. This two-photon process occurs due to internal two-photon photoemission in the e-C followed by acceleration of these electrons in both the image charge field and the SP field within the e-C layer. In addition, there is Schottky barrier lowering at the Au-vacuum interface, which in combination with the acceleration allows for two-photon generated electrons with initial kinetic energies below the work function to escape to vacuum. This result opens the way for enhancing photoemission electron yields while operating below the damage threshold of the material.

10102-28, Session 7

Exciton Mott transition in GaAs studied by terahertz spectroscopy *(Invited Paper)*

Fumiya Sekiguchi, Changsu Kim, Hidefumi Akiyama, Ryo Shimano, The Univ. of Tokyo (Japan)

Mott transition, i.e. the metal-insulator transition (MIT) driven by the change of the electron interactions, has been one of the central problems in condensed matter physics. Among various material systems, an ensemble of excitons, hydrogen-like bound states of electron-hole pairs, offers an intriguing platform to test the Mott's original argument on MIT in an array of one-electron atoms. The understanding of exciton Mott transition (EMT) is also crucial for the application of semiconductor optoelectronic devices, while the nature of EMT at the low temperature regime has remained uncovered. From the fundamental point of view, physics of EMT is closely related to the theoretically anticipated crossover between the exciton Bose-Einstein condensation and the electron-hole (e-h) BCS state. In this

study, we revealed the nature of EMT in bulk GaAs by using optical-pump and THz probe spectroscopy. By resonantly exciting 1s excitons, we avoided the photo-injection of excess energy to the e-h system, and realized a low temperature and high density e-h state. By developing a nonlinear terahertz spectroscopy technique which sensitively detects the e-h correlation, we discovered the presence of an anomalous correlated metal phase on the verge of Mott transition. The observed anomaly is clearly shown to stem from the e-h pair correlation sustaining in a metal phase above the EMT, which may be viewed as preformed e-h Cooper pair state. The ultrafast dynamics of the phase transition from exciton gas to e-h correlated metal will be discussed.

10102-29, Session 7

Ultrafast infrared spectroscopy at the nanoscale

Max Eisele, neaspec GmbH (Germany)

The infrared spectral range is home to an extremely rich and diverse array of low-energy excitations, e.g. phonons, plasmons and excitons, which strongly influence the physical properties of solids. Fourier-transform infrared spectroscopy (FTIR) or ultimately field-resolved detection of mid-infrared light pulses (terahertz spectroscopy) has turned time-resolved spectroscopy in the infrared spectral range into a powerful tool for studying and controlling dynamics of low-energy excitations on ultrafast timescales. However, the spatial resolution of far-field infrared studies is inherently limited to the scale of the probing wavelength by diffraction, making it impossible to extract material characteristics at the nanoscale. Scattering-type scanning near-field optical microscopy (s-SNOM) offers the possibilities to resolve this shortcoming by utilizing the strong confinement of optical near-fields at the apex of sharp metal tips.

This talk introduces and summarizes the latest results and innovations in the field of ultrafast nano-spectroscopy. Using a combination of time-resolved mid-infrared spectroscopy and s-SNOM, these microscopes achieve an unprecedented spatial resolution of 10-nm in combination with a temporal resolution of up to 10-fs. This unique approach opens the door to a new dimension in experimental solid-state physics in which the local, intrinsic response of ultrafast low-energy elementary excitations can directly be traced in space and time. The ultrafast near-field microscope has already been used to observe ultrafast carrier dynamics in bulk and nano-sized semiconductors, femtosecond dynamics in single layer materials as well as pump-induced transitions in strongly correlated materials, granting key insight into the dynamics of, e.g. electron at the nanoscale.

10102-30, Session 7

Terahertz time-domain spectroscopy of magnons in antiferromagnetic MnF2

Alan D. Bristow, Derek A. Bas, Pavel Borisov, West Virginia Univ. (United States); David Lederman, West Virginia Univ. (United States) and Univ. of California, Santa Cruz (United States)

Antiferromagnets are an important class of ordered spin systems, common in spintronic applications and providing a testbed for studying magnetism. Recently, the injection of magnons – coherent spin waves – has been explored by broadband terahertz pulses in antoferromagnets, such as MnO. Here, terahertz time-domain spectroscopy is used to detect magnon resonances in MnF2, which is a model antiferromagnet with uniaxial anisotropy and a Néel temperature of 67 K. Temperature dependence of a one-magnon resonances is examined from 5 K to 70 K. The center frequency of the one-magnon is recorded below the Néel temperature and fit to a Brillouin function. It is found that the degree of correlation between neighboring spins is j = 1.1. Namely, a weak correlation and appropriately modeled by mean-field theory befitting this simple system. From low temperature to room temperature, a two-magnon resonance is observed to broaden and strengthen as the temperature increases. Two-magnon modes arise due to zone-edge magnons being stimulated with -k and +k momenta and do not require magnetic ordering. Over this same temperature range, THz transients are used to monitor the time-of flight through the crystal, the refractive index, the internal energy and the heat capacity. Overall these quantities decrease with decreasing temperature, with behavior that falls into three regimes: a thermal dominated region above the Néel temperature, a magnetic regime below the Néel temperature; and a hyperfine interaction region at temperatures below 6 K. The latter is the first direct observation of the hyperfine interaction using terahertz time-domain spectroscopy.

10102-31, Session 7

In-situ THz spectroscopy on lead halide perovskite film for monitoring transient crystallization phase

SaeJune Park, Yeong Hwan Ahn, Ajou Univ. (Korea, Republic of)

In the past few years, perovskite film has been considered as a promising materials for solar cell devices due to its outstanding performance. To maximize the perovskite solar cell performance, it is necessary to understand the crystallization mechanism of perovskite film. In this study, we monitored the crystallization and decrystallization of the lead halide perovskite (MAPbI3-xClx) film under thermal annealing and UV-laser exposure processes by using in-situ terahertz time-domain spectroscopy. The strength of vibrational resonances in THz frequency range is found to be a good indicator of perovskite crystallinity. We measured the THz spectra as we annealed the perovskite film at various temperatures in order to achieve the degree of crystallization, i.e., the transition of perovskite structure from the intermediate phase to the tetragonal phase. In addition, we investigated the UV-laser-induced phase transition of the perovskite film. Because it is widely known that UV light illumination on perovskite film tends degrade the perovskite cell efficiency, its influence on the crystallization is our primary concern. Surprisingly, the crystallization phase increases for 10 min, until it starts to degrade over a couple of hours. We also studied the transient transport properties of the films under UV illumination. The correlation between the degree of crystallization (obtained from THz transmission) and the transport parameters exhibited the electric percolation threshold behaviors in the perovskite films. These information are expected to be crucial for optimizing the fabrication method of perovskite solar cell.

10102-32, Session 7

Spectroscopy with ultra-strong coupling of THz metasurfaces to spin-split heavy-hole cyclotron resonances in strained Ge quantum wells

Janine Keller, Giacomo Scalari, Curdin Maissen, Gian Lorenzo Paravicini-Bagliani, ETH Zürich (Switzerland); Johannes Haase, Paul Scherrer Institut (Switzerland); Michele Failla, Maksym Myronov, David R. Leadley, James Lloyd-Hughes, Univ. of Warwick (United Kingdom); Jérôme Faist, ETH Zürich (Switzerland)

We study the ultra-strong coupling (USC) of Landau level transitions in strained Germanium quantum wells (sGe QW) to THz metasurfaces. The spin-splitting of the heavy-hole cyclotron resonance in sGe QWs due to the Rashba spin-orbit interaction in magnetic field offers an excellent platform to investigate ultra-strong coupling to a non-parabolic system. THz split ring resonators can be tuned to coincide with the single cyclotron transition (around 0.4 THz and a magnetic field of 1.5 T) or the spin-resolved transitions of the sGe QWs (at 1.3 THz and 4.5 T). Coupling to the single cyclotron yields a normalized USC rate of 25%, resulting from fitting with a Hopfield-like Hamiltonian model. Coupling to two or three cyclotron resonances in sGe QWs lead to the observation of multiple polaritons branches, one polariton branch for each oscillator involved in the system. An adaption of the theory allows to also describe this multiple-oscillator system and to determine the coupling strengths. The different Rabi-splittings for the multiple cyclotrons coupling to the same resonator mode relate to the underlying differences in the material. Furthermore, the visibility of an additional transition, possibly a light hole transition with very low carrier density, is strongly enhanced due to the coupling to the LC-resonance with a normalized strong coupling ratio of 4.7%. Future perspectives include controlling spin-flip transitions in USC and studying the impact of non-parabolicity on the ultra-strong coupling physics.

10102-33, Session 7

Transient GaAs plasmonic metasurfaces at terahertz frequencies

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We demonstrate a transient GaAs plasmonic metasurface at terahertz (THz) frequencies. The macroscopic metasurface is generated through ultrafast all-optical creation of spatially modulated carrier density profiles in a deep-subwavelength GaAs film. The switch-on of the transient plasmon mode (within 500 femtoseconds) is determined by the GaAs effective electron mass and electron-phonon interaction, and is revealed by structured-optical pump THz probe spectroscopy. The decay of this mode (~1 nanosecond) is governed by the carrier recombination time and can potentially be engineered. Using various pump fluences we can modulate the carrier density, thereby observing a wide tuning of the electric dipole resonance of the transient GaAs metasurface from 0.5 THz to 1.7 THz. The transient GaAs-based plasmonic metasurface provides a pathway for the ultrafast modulation of THz waves. This could potentially enable a new class of tunable THz devices in the linear and nonlinear regimes.

10102-34, Session 7

Impact ionization dynamics in silicon by a picosecond THz electric field pulses

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Metallic antenna arrays fabricated on high resistivity silicon are used to localize and enhance the incident THz field resulting in high electric field pulses with peak electric field strength reaching several MV/cm on the silicon surface near the antenna tips. In such high electric field strengths high density of carriers are generated in silicon through impact ionization process. The high density of generated carriers induces a change of refractive index in silicon. By measuring the change of reflectivity of tightly focused 800 nm light, the local density of free carriers near the antenna tips is measured. Using the NIR probing technique, we observed that the density of carriers increases by over 8 orders of magnitude in a time duration of approximately 500 fs with an incident THz pulse of peak electric field strength 700 kV/cm. This shows that a single impact ionization process is happening in a time duration of less than 20 fs. The measurement is repeated by exciting the sample with an optical pump beam at a wavelength of 400 nm. The optical pump sets the initial free carrier density before the THz-induced impact ionization. The measurements show that the carrier generation mechanism depends on the initial free carrier density which confirms that the carrier generation mechanism is impact ionization, rather than the alternative carrier generation mechanism in high electric field, i.e. Zener tunneling. Finally this technique can be extended to investigate carrier dynamics in other semiconductors.

10102-35, Session 8

From Mahan excitons to Landau levels at high magnetic fields: 2DFT spectroscopy reveals hidden quantum correlations *(Invited Paper)*

Denis Karaiskaj, Univ. of South Florida (United States)

Two-dimensional electron gases have been the subject of research for decades. Modulation doped GaAs quantum wells in the absence of magnetic fields exhibit interesting many-body physics such as the Fermi edge singularity or Mahan exciton and can be regarded as a collective excitation of the system.

Under high magnetic fields Landau levels form which have been studied using transport and optical measurements. Nonlinear coherent two-dimensional Fourier transform (2DFT) spectroscopy however provides new insights into these systems. We present the 2DFT spectra of Mahan Excitons associated with the heavy-hole and light-hole resonances observed in a modulation doped GaAs/AlGaAs single quantum well [1]. These resonances are observed to be strongly coupled through many-body interactions.

The 2DFT spectra were measured using co-linear, cross-linear, and co-circular polarizations and reveal striking differences. Furthermore, 2DFT spectra at high magnetic fields performed at the National High Magnetic Field Lab (NHMFL) in Tallahassee, Florida will be discussed. The spectra exhibit new features and peculiar line shapes suggesting interesting underlying physics.

[1] J. Paul, C. E. Stevens, C. Liu, P. Dey, C. McIntyre, V. Turkowski, J. L. Reno, D. J. Hilton, and D. Karaiskaj, Phys. Rev. Lett.116, 157401 (2016).

10102-36, Session 8

Four-wave mixing response of solution-processed CH3NH3PbI3 thin films *(Invited Paper)*

Kimberley C. Hall, Dalhousie Univ. (Canada); Sam A. March, Dalhousie Univ (Canada); Drew Riley, Charlotte Clegg, Ian Hill, Dalhousie Univ. (Canada)

The organic-inorganic perovskite semiconductors, for which methylammonium lead iodide is the prototypical material combination, have attracted considerable attention in recent years due to the potential for developing low-cost alternatives to conventional silicon solar cell technology. Perovskite solar cell efficiencies have recently reached 22% [1]. Despite this progress, the underlying photophysical properties are not well understood, due in part to strong disorder intrinsic to the solution-processed films. Here we report the application of four-wave mixing techniques to CH3NH3PbI3 [2]. While the dephasing time within the high-temperature tetragonal phase is not resolvable using the 40 fs laser excitation pulses, within the low-temperature orthorhombic phase (for 160 K and below), we observe a dephasing time for free carriers of 200 fs. Our experiments show that, at carrier densities appropriate for solar cell operation, carrier-carrier scattering is much weaker in perovskite than in III-V semiconductors such as GaAs and low-temperature-grown GaAs, shedding light on the long dephasing times observed. The weak interactions between charge carriers are attributed to carrier localization tied to the complex disorder in perovskite materials, for which point defects and grain boundaries contribute [3] together with the freedom of motion of the methylammonium cations [4]. Our findings shed light on the dominant

scattering processes for carriers within solar cell devices based on this system.

[1] http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

[2] S. A. March et al., arXiv:1602.05186 [cond-mat.mtrl-sci] (2016).

[3] Yin et al. Appl. Phys. Lett. 104, 063903 (2014).

[4] Bakulin et al. J. Phys. Chem. Lett. 6, 3663 (2015).

10102-37, Session 8

High fidelity transfer and storage of photon states in a single nuclear spin *(Invited Paper)*

Sen Yang, The Chinese Univ. of Hong Kong (Hong Kong, China)

Long-distance quantum communication requires photons and quantum nodes that comprise qubits for interaction with light and good memory capabilities, as well as processing qubits for the storage and manipulation of photons. Owing to the unavoidable photon losses, robust quantum communication over lossy transmission channels requires quantum repeater networks. A necessary and highly demanding prerequisite for these networks is the existence of quantum memories with long coherence times to reliably store the incident photon states. Here we demonstrate the high-fidelity (?98%) coherent transfer of a photon polarization state to a single solid-state nuclear spin that has a coherence time of over 10 s. The storage process is achieved by coherently transferring the polarization state of a photon to an entangled electron–nuclear spin state of a nitrogen–vacancy center in diamond. The nuclear spin-based optical quantum memory demonstrated here paves the way towards an absorption-based quantum repeater network.

10102-38, Session 8

Unraveling electron and hole relaxation dynamics in colloidal CdTe nanorods: a two-dimensional electronic spectroscopy study

Tatjana Stoll, Federico Branchi, Julien Rehault, Politecnico di Milano (Italy); Ilka Kriegel, Istituto Italiano di Tecnologia (Italy); Francesco Scotognella, Politecnico di Milano (Italy); Francesco Tassone, Istituto Italiano di Tecnologia (Italy); Giulio Cerullo, Politecnico di Milano (Italy)

In the present work we study ultrafast exciton dynamics in colloidal cadmium telluride (CdTe) nanorods by two-dimensional electronic spectroscopy (2DES). 2DES is a very versatile technique combining ultrahigh temporal (15 fs in the case of our study) and spectral resolution in both excitation and detection, which allows us to study at one glance the simultaneously excition and probing of the lowest three excitonic transitions (S1, S2 and S3). By probing an ultrafast decay of the S2 transition and the correlated rise of S1, we directly observe the relaxation of hot holes from the 1?3/2 to the 1?1/2 state (S2?S1) with 30±10 fs time constant; an observation barely possible in conventional pump probe due to the spectral superposition of the transitions and the concomitant very fast relaxation timescales. Moreover, we extract a direct hole relaxation from the higher lying S3 state to the ground state S1 omitting the transition via S2, by disentangling the overlapping bleach and excited state induced energy level shifts after excitation of S3. This is a peculiar finding of the CdTe nanorods probably related to the nature of the S3 transition peaking away from the ? point ($k_z \neq 0$). The understanding of ultrafast photophysics in colloidal semiconductor nanocrystals, as CdTe nanorods, will be the key for an improved design of complex hybrid nanostructures used in optoelectronics, which aim to separately control the electron and hole relaxation pathways.

10102-39, Session 8

Nonlinear excitation of single quantum emitters in hexagonal boron nitride

Andreas W. Schell, Kyoto Univ. (Japan); Trong Toan Tran, Igor Aharonovich, Univ. of Technology, Sydney (Australia); Hideaki Takashima, Shigeki Takeuchi, Kyoto Univ. (Japan)

Recently, two-dimensional materials have gained much interest for various applications in nanophotonics and quantum optics, as they possess a strong luminescence and are able to host single quantum emitters. Excitation of quantum emitters via a two-photon process can be employed for high resolution imaging and has applications in quantum optics. Here, we present one- and two-photon excitation of single defects in hexagonal boron nitride (hBN) and analyse the properties of the emitted light [1]. We find clear antibunching signals that prove the single emitter character in both excitation cases. To gain further knowledge, we also obtain saturation curves. From a comparison of one- and two-photon case insights about the level structure of the defects can be obtained. These results will not only help the fundamental understanding of defects in hBN, but also help to introduce this class of emitters in optical imaging, as the defects in hBN are of small spatial extend, photostable and emit their fluorescence well in the wavelength region of the biological optical window.

[1] A. W. Schell et al. arXiv:1606.09364 (2016)

10102-40, Session 8

Dynamical stabilization of a polariton Rabi oscillator in the ground and inverted stationary states

Nina S. Voronova, National Research Nuclear Univ. MEPhI (Russian Federation) and Russian Quantum Ctr. (Russian Federation); Andrei A. Elistratov, All-Russia Research Institute of Automatics (Russian Federation); Yurii E. Lozovik, Institute for Spectroscopy, Russian Academy of Sciences (Russian Federation)

The reported work contains a study of the effects of photon-exciton energy detuning, interactions, exciton cw pumping and non-linear losses on the temporal dynamics of polariton Rabi oscillations in a semiconductor microcavity. For a conservative system without gain and loss, we show that non-zero detuning between the photon and exciton modes may bring the system into a regime with running relative phase, which we connect with internal Josephson effect in conventional bosonic Josephson junctions [PRL 115, 186402 (2015)]. For the driven-dissipative case, we demonstrate that the interplay between the non-linearities in the exciton component leads to the regimes reminiscent of van der Pol oscillator with amplitude-dependent damping and to the appearance of a non-trivial “inverted” stationary state, where the upper polariton branch is macroscopically occupied, while the lower polariton branch becomes essentially empty. This state is sustained despite the strong leakage of particles from the upper polariton branch [PRB 94, 045413 (2016)]. Both the effects of the internal Josephson regime and the stabilization of inverted pendulum state reminiscent of classical Kapitza pendulum are essentially non-linear, dependent on initial conditions and external parameters. We show that these effects may combine if the density of particles is large enough. Additionally, we provide the discussion on experimental observation of the predicted phenomena.

10102-41, Session 9

Subcycle quantum physics *(Invited Paper)*

Alfred Leitenstorfer, Univ. Konstanz (Germany)

A time-domain approach to quantum electrodynamics is presented, covering the entire mid-infrared and terahertz frequency ranges. Ultrabroadband electro-optic sampling with few-femtosecond laser pulses allows direct detection of the vacuum fluctuations of the electric field in free space [1,2]. Besides the Planck and electric field fundamental constants, the variance of the ground state is determined solely by the inverse of the four-dimensional space-time volume over which a measurement or physical process integrates. Therefore, we can vary the contribution of multi-terahertz vacuum fluctuations and discriminate against the trivial shot noise due to the constant flux of near-infrared probe photons. Subcycle temporal resolution based on a nonlinear phase shift provides signals from purely virtual photons for accessing the ground-state wave function without amplification to finite intensity.

Recently, we have succeeded in generation and analysis of mid-infrared squeezed transients with quantum noise patterns that are time-locked to the intensity envelope of the probe pulses. We find subcycle temporal positions with a noise level distinctly below the bare vacuum which serves as a direct reference. Delay times with increased differential noise indicate generation of highly correlated quantum fields by spontaneous parametric fluorescence. Our time-domain approach offers a generalized understanding of spontaneous emission processes as a consequence of local anomalies in the co-propagating reference frame modulating the quantum vacuum, in combination with the boundary conditions set by Heisenberg's uncertainty principle.

[1] C. Riek et al., Science 350, 420 (2015)

[2] A. S. Moskalenko et al., Phys. Rev. Lett. 115, 263601 (2015)

10102-42, Session 9

Quantum design of coherent x-rays for imaging at the space-time resolution extreme *(Invited Paper)*

Tenio Popmintchev, JILA (United States)

Nonlinear optics revolutionized the ability to create directed, laser-like light particularly in the regions where lasers based on conventional population inversion are not practical. New breakthroughs in attosecond extreme nonlinear optics promise a similar revolution in the X-ray regime.

In this talk, I will discuss the fundamental quantum physics and the phase matching limits of high order harmonic generation in the context of creating coherent X-ray waveforms in the soft X-ray region that can be tailored at the moment of generation. Such a versatile designer light is ideal for 4D studies of various bio- and nano-materials systems with attosecond temporal and nanometer spatial resolution, as well as with element specificity. I will also discuss the path forward for generating bright coherent X-ray beams from a laboratory-scale apparatus at photon energies of 10 keV and greater with unprecedented attosecond-to-zeptosecond pulse durations, and with arbitrary spectral, temporal shapes, and polarization states. A fully spatially and temporally coherent version of the Roentgen X-ray tube with exquisite quantum control of the properties of the soft and hard X-ray light may be possible.

1. T. Popmintchev, et al., Nature Photonics 4, 822 (2010); Science 336, 1287 (2012).

2. D. Popmintchev, et al., Science 350, 1225 (2015).

3. T. Fan, et al., PNAS 112, 14206 (2015).

10102-43, Session 9

Sub-cycle THz nanoscopy and ultrafast STM with Angstrom-scale spatial resolution *(Invited Paper)*

Tyler Cocker, Dominik Peller, Markus A. Huber, Markus Plankl, Fabian Mooshammer, Univ. Regensburg (Germany); Max Eisele, Univ. of Regensburg (Germany); Ping Yu, Univ. Regensburg (Germany); Leonardo Viti, CNR-NANO (Italy); Robert E. Marvel, Richard F. Haglund Jr., Vanderbilt Univ. (United States); Miriam S. Vitiello, CNR-NANO (Italy); Jascha Repp, Rupert Huber, Univ. Regensburg (Germany)

Here, we demonstrate how few-cycle, phase-stable terahertz (THz) pulses can be coupled to sharp metal tips to enable simultaneous femtosecond time resolution and sub-angstrom spatial resolution.

(i) We combine ultrafast field-resolved multi-THz spectroscopy with scattering-type near-field scanning optical microscopy to access sub-cycle dynamics on the nanoscale. We trace the oscillating electric field from a (10 nm)^3 volume on the surface of an indium arsenide nanowire with 10 fs temporal resolution, revealing the ultrafast formation of a carrier depletion layer on the nanowire surface [1]. Furthermore, we apply ultrafast multi-THz nanoscopy to vanadium dioxide nanobeams and observe a previously unseen correlation between the local steady-state phase-switching susceptibility and the ultrafast response to below-threshold photoexcitation [2]. Finally, we explore the ultrafast formation of mid-infrared surface plasmons in heterostructures based on novel van der Waals materials [3].

(ii) Utilizing the concept of THz scanning tunneling microscopy [4], we explore an unprecedented, state-selective tunneling regime where the peak of a THz electric-field waveform opens an otherwise forbidden tunneling channel through a single molecular state. The peak field of the THz pulse removes a single electron from an individual pentacene molecule's highest occupied molecular orbital within a time window faster than and oscillation cycle of the THz probe. We employ this process to record ~100 fs snapshot images of the orbital structure with sub-angstrom spatial resolution and reveal coherent molecular vibrations at THz frequencies directly in the time domain [5].

[1] M. Eisele et al. Nature Photon. 8, 841 (2014).

[2] M. A. Huber et al. Nano Lett. 16, 1421 (2016).

[3] M. A. Huber et al. Submitted (2016).

[4] T. L. Cocker et al. Nature Photon. 7, 620 (2013).

[5] T. L. Cocker et al. Submitted (2016).

10102-44, Session 10

Observation of ultrafast temporal evolution of symmetry in short-pulsed laser induced transient states of matter

Joy Garnett, Halina Krzyzanowska, Andrey Baydin, Norman H. Tolk, Vanderbilt Univ. (United States)

In condensed matter physics, ultrafast photoexcitation has been shown to result in modification of macroscopic material properties, sometimes involving phase changes, on a subpicosecond time scale. In semiconductors, irreversible non-thermal solid-to-liquid structural transitions have been demonstrated at high laser fluences.

In the pump-probe experiments reported here, we observe a striking continuously varying low-fluence pump-induced time-dependent structural symmetry modification in intrinsic gallium arsenide (GaAs) using a probe that produces femtosecond polarization-resolved second harmonic generation (f-PRSHG) data. SHG spectroscopy is particularly suited to monitor symmetry changes since its magnitude is governed by the nonlinear optical susceptibility tensor whose elements are determined by the underlying material symmetry. Conceptually, these experiments seek to provide insight into the details of the time evolution of symmetry arising from laser induced transient states of matter in GaAs. Overall, the basic explanation of these experimental observations is that as a result of the photoinduced electronic excitation, many electrons, including bond electrons are excited to higher states. This results in subpicosecond changes in the local anharmonic potential and produces a changing nonlinear polarization response thus accounting for the nonthermal time dependent symmetry changes. Clearly, our approach may be easily extended to many different crystalline materials with different levels of defects, dopants and stresses to fully characterize the time dependent behavior of laser induced transient states in material systems.

10102-45, Session 10

Single CdTe nanowire optical correlator

Chenguang Xin, Limin Tong, Zhejiang Univ. (China)

Based on the transverse second harmonic generation (TSHG) in a subwavelength-diameter CdTe nanowire, we demonstrate an ultracompact optical correlator for femto-second pulses measurement. Benefitted from the high second-order nonlinearity and large refractive index of CdTe, input pulse energy goes down to few femtojoules per pulse. The CdTe nanowire with single crystal structure was synthesized by a thermal evaporation process and suspended across a slit of two MgF2 substrates. The 1064-nm pulses were firstly split into two traces and coupled into the nanowire from both ends using fiber-taper-assisted evanescent coupling. Optical path difference between two traces was adjusted carefully to overlap counterpropagating pulses around the central area of the nanowire. As required by wave-vector matching, transverse second harmonic (TSH) light emitted in the direction perpendicular to the axis of nanowire. Then the TSH spatial image was recorded and converted to the temporal profile of the input pulses. With an ultralow input energy, this correlator may find applications spanning from on-chip optical communication, biological medicine, to ultra-compact laser spectroscopy. The large refractive index and low-loss transmission window (~1 ?m to about 30 ?m) of the CdTe crystal make it can be in principle operated beyond a large spectral range.

10102-46, Session 10

Influence of SOD on THG for femtosecond laser pulse

Vyacheslav A. Trofimov, Pavel S. Sidorov, M.V. Lomonosov Moscow SU (Russian Federation)

THG is used nowadays in many practical applications such as a substance diagnostics, and imaging of biological objects and et?. Therefore, understanding of THG features is urgent problem. Below we analyze THG efficiency of a femtosecond laser pulse propagating in a medium with cubic nonlinear response. Consideration is based on computer simulation of the laser pulse propagation with taking into account a self- and cross-modulation of interacting waves, and their SOD, and phase mismatching. Moreover, we analyze an influence of a non-homogeneous distribution of the phase mismatching along a coordinate of laser pulse propagation. In this case, a phase matching occurs only in narrow area of longitudinal coordinate. Due to strong self- and cross- modulation of interacting waves it is possible to manage effective THG.

Using the frame-work of long pulse duration approximation and plane wave approxima-tion as well as an original approach we write the explicit solution of Schrödinger equa-tions describing the THG of femtosecond pulse. It should be stressed, that the main feature of our approach consists in conservation laws using corresponding to wave interaction process.

10102-66, Session 10

Non-perturbative twist of attosecond extreme-ultraviolet vortex beams

Carlos Hernandez-Garcia, Laura Rego, Julio San Román, Univ. de Salamanca (Spain); Antonio Picón, Argonne National Lab. (United States); Luis Plaja, Univ. de Salamanca (Spain)

Optical vortices, i.e. twisted beams carrying orbital angular momentum (OAM), offer a unique capability to harness light matter-interaction processes by adding a supplementary degree of freedom. Recently, high-order harmonic generation (HHG) has been proven to produce extreme-ultraviolet (XUV) attosecond vortices from the nonlinear conversion of infrared twisted beams, extending the applications of optical vortices (communication, spectroscopy, lithography) down to the nano-scale. Previous works demonstrated a linear scaling law of the vortex charge with the harmonic order. In a recent breakthrough (L. Rego et al. Phys. Rev. Lett. in press) we demonstrate that this simple law hides an unexpectedly rich scenario for the build-up of OAM due to the non-perturbative behavior of HHG.

We perform advanced quantum simulations of OAM-HHG, to show that if non-pure vortex drivers are used, the OAM content of the twisted attosecond beams is dramatically increased, due to the non-perturbative intrinsic phase of the HHG process. We explore the underlying mechanisms for this phenomena and derive a general conservation rule for the non-perturbative OAM build-up, that allow us to tune the OAM content of the XUV vortex beams. In particular, our results are very relevant for vortex drivers with only a fractional modal contamination, and thus essential for understanding realistic OAM-HHG experiments, where non-pure vortices are typically used.

Our results show that the laser-matter coupling with OAM beams is a very sensitive probe of the non-perturbative aspects of strong-field interactions, paving the route for the next generation of high-resolution XUV/x-ray diagnostic tools for fundamental studies and applications.

10102-47, Session 11

Time-resolved photoemission microscopy of semiconductor heterostructures *(Invited Paper)*

Michael K. L. Man, Athanasios Margiolakis, Skylar Deckoff-Jones, Takaaki Harada, E. Laine Wong, Bala Murali Krishna Mariserla, Julien Madeo, Andrew Winchester, Okinawa Institute of Science and Technology Graduate Univ. (Japan); Sidong Lei, Robert Vajtai, Pulickel M. Ajayan, Rice Univ. (United States); Keshav Dani, Okinawa Institute of Science and Technology Graduate Univ. (Japan)

The ability to make movies of the dynamics of photoexcited electrons in complex, heterostructure materials with simultaneous high spatial and temporal resolution would benefit future development of nano-engineered photoactive devices. To date, optical techniques provide excellent temporal resolution, but poor spatial resolution. Alternately, electron microscopy techniques achieve excellent spatial resolution, but are limited in temporal resolution. Over the past decade, time-resolved photoemission electron microscopy (TR-PEEM) techniques have combined the temporal resolution of ultrafast optics with the spatial resolution of electron microscopy to access electron dynamics in metallic structures or semiconductor wafers, but heterostructure samples have remained beyond reach. Here, we extend TR-PEEM techniques to semiconductor heterostructures to make movies of the ultrafast dynamics of photocarriers in energy, momentum, space and time as electrons traverse across heterostructure boundaries. At the instant of photoexcitation in a type-II GaAs/InSe heterostructure, spectrally resolved images of the sample reveal the highly non-equilibrium distribution of photoexcited carriers in space and energy. At later time delays, we image the spatial flow of electrons from high energy GaAs states to low energy InSe states, thus making a movie of the fundamental operating phenomena in a solar cell. In doped GaAs wafers, by rapidly screening internal electric fields with photoexcited carriers, we watch the resulting transport of carriers between the bulk and surface with spatial, energy, momentum and time resolution. Our observed electron dynamics provide insight into the operation of various semiconductor optoelectronic devices, and suggest possibilities for future direction.

10102-48, Session 11

Control of interlayer valley excitons in atomically-thin MoSe2-WSe2 heterostructures *(Invited Paper)*

John Schaibley, The Univ. of Arizona (United States)

Atomically thin semiconductors, such as monolayer MoSe2 and WSe2, have emerged as exciting optoelectronic materials, with novel spin-valley electronic physics and excitons that are strongly bound at room temperature. It has recently been shown that these materials can form the basis for atomically thin p-n junctions, transistors, light emitting diodes, and low threshold nanolasers. In this presentation, I will discuss optoelectronics and spin effects in heterostructures of MoSe2 and WSe2, with type-II band alignment, with the lowest conduction band in the MoSe2 layer, and the highest valence band in the WSe2 layer. Upon optical excitation, electrons transfer to the MoSe2 layer and holes transfer to the WSe2 layer. Due to the strong attractive Coulomb interaction between these spatially separated layers, interlayer excitons can form which have many similarities to the spatially indirect excitons of coupled GaAs quantum wells. However, unlike the coupled quantum well system, here the constituent electrons and holes are located in momentum space valleys on the edge of the Brillouin zone. The conduction and valence band valley alignment can be tuned by twist angle between layers to realize optically bright interlayer excitons with an optical selection rule allowing for optical control of the valley degree of freedom. I will discuss the dynamics and spin-valley effects of these bright interlayer excitons.

10102-49, Session 11

Excitonic linewidth and coherence lifetime in monolayer transition metal dichalcogenides

Malte Selig, Gunnar Berghäuser, Technische Univ. Berlin (Germany); Archana Raja, Coulumbia Univ. (United States); Philipp Nagler, Christian Schüller, Univ. Regensburg (Germany); Tony F. Heinz, Coulumbia Univ. (United States); Tobias Korn, Alexey Chernikov, Univ. Regensburg (Germany); Ermin Malic, Chalmers Univ. of Technology (Sweden); Andreas Knorr, Technische Univ. Berlin (Germany)

Due to strong Coulomb-induced phenomena, monolayers of transition metal dichalco-

genides (TMDs) have attracted much attention. Because of their complex electronic band-structure, the optical response is dominated by a variety of optically bright and dark excitonic states.

Here, we focus on a discussion of the linewidth of these resonances: The theoretical approach is based on a Heisenberg equation of motion formalism combined with the tight binding approximation and includes radiative decay and exciton phonon interaction. The experiments are based on optical reflectance and luminescence measurements.

We focus on two representative materials, MoSe2 and WSe2 which differ significantly in the energetically position of the dark exciton states with respect to the bright states. Since in MoSe2 the dark states lie energetically above the bright ones, they are only weakly accessible via phonon scattering, and thus do not contribute significantly to the homogeneous linewidth.

The situation turns out to be entirely different in WSe2 : Here, the dark exciton states lie energetically below the bright states resulting in an efficient relaxation into these states even at low temperatures due to phonon emission. Exemplary, in WSe2 we find a temperature independent broadening due to radiative decay of 3 meV and a superlinear increasing non-radiative broadening, which is about 30 meV at room temperature.

This corresponds to a coherence lifetime of 20 fs, which is one order of magnitude faster than in conventional 2D materials.

10102-50, Session 11

Enhanced optical activity of atomically-thin MoSe2 proximal to nanoscale plasmonic slot-waveguides

Maex Blauth, Julian Harms, Maximilian Prechtl, Walter Schottky Institut (Germany); Jonathan J. Finley, Walter Schottky Institut (Germany) and Nanosystems Initiative Munich (Germany); Michael Kaniber, Walter Schottky Institut (Germany)

For practical nanoscale photonic applications, energy efficient light sources with small footprints are of central importance. In recent years, atomically thin, two-dimensional semiconductors have attracted strong interest, both in the field of nano-optics and nano-electronics. Combining these novel materials with nano-plasmonic waveguides potentially opens the way to build integrable plasmonic light sources with subwavelength footprints, offering strong potential for nano-optics and sensing.

Here, we present numerical simulations and optical results obtained from mechanically exfoliated monolayer MoSe2 crystals proximal to plasmonic waveguides. Detailed numerical studies on hybrid plasmon polariton waveguides and slot waveguides are presented. Our optical measurements on slot waveguides coupled to monolayer MoSe2, conducted at cryogenic temperatures show the appearance of spectral features between 1.55 eV and 1.61 eV, at the low-energy side of the pristine MoSe2 emission, consistent with recent demonstrations of single photon emitters in this material. We find degrees of polarization of up to 40% which are in good agreement with simulations that indicate Purcell-enhanced emission into the supported plasmonic modes with a transverse mode volume of 0.02 ?^(-2). As a proof of emission coupling into these modes, we present optical propagation length measurements revealing L_SPP=(380±60)nm, thereby, proving the plasmonic character of the observed luminescence.

Finally, we evaluate the prospects of building electrically pumped nanoscale integrated coherent light sources using atomically thin semiconductor layers as gain material, reveal unexpectedly large confinement factors of up to 10, and demonstrate stability against fabrication imperfections and threshold gain values for lasing of ~10^4/cm.

10102-64, Session PWed

Nanoplasmonic antenna for carrier-envelope-phase detection

Shawn R. Greig, Abdulhakem Y. Elezzabi, Univ. of Alberta (Canada)

We present a detailed investigation of a compact, solid-state carrier-envelope-phase (CEP) detector for operation with ultrafast laser pulses with a central wavelength of 800nm. The detector consists of a nanoplasmonic Au nanoantenna embedded in a Si substrate. The nanoantenna consists of half a bowtie and a flat transmission line separated by a gap of 20nm. When the device is illuminated with an ultrafast laser pulse, there is an asymmetric nanoplasmonic electric field between the tip of the bowtie and the flat transmission line. This asymmetry allows for ponderomotive acceleration of electrons that are photogenerated within the Si present in the gap of the nanoantenna. As such, the electrons will be accelerated to either the left or right electrode of the antenna. The ponderomotive electron acceleration process is extremely sensitive to the instantaneous phase of the electric field when the electron is generated. Therefore, the generated electrons will be accelerated either to the right or left electrode depending on the instant that they are generated. By observing the difference in current collected between the two electrodes the CEP of the incident pulse can be determined. Notably, this device has a compact footprint of 120?200nm.

10102-65, Session PWed

Interferometric measurement of refractive index modification in a single-mode microfiber

Farid Ahmed, Vahid Ahsani, Martin B. G. Jun, Univ. of Victoria (Canada)

Efficient and cost effective measurement of the refractive index profile in an optical fiber is a significant technical job to design and manufacture in-fiber photonic devices and communication systems. For instance, to design fiber gratings, it is required to estimate the refractive index modulation to be inscribed by the fabrication apparatus such as ultraviolet or infrared lasers. Mach-Zehnder interferometer (MZI) based quantification of refractive index (RI) change written in single mode microfiber by femtosecond laser radiation is presented in this study. The MZI is constructed by splicing a microfiber (core diameter: 3.75 ?m, cladding diameter: 40 ?m) between standard single mode fibers. To measure the RI inscribed by infrared femtosecond laser, 200 ?m length of the core within the MZI was scanned with laser radiation. As the higher index was written within 200 ?m length of the core, the transmission spectrum of the interferometer displayed a corresponding red shift. The observed spectral shift was used to calculate the amount of RI change inscribed by the femtosecond irradiation. For the MZI length of 3.25 mm, and spectral shift of 0.8 nm, the calculated refractive index was found to be 0.00022. The reported results display excellent agreement between theory and experimental findings. Demonstrated method provides simple yet very effective on-site measurement of index change in optical fibers. Since the MZI can be constructed in diverse fiber types, this technique offers flexibility to quantify index change in various optical fibers.

10102-68, Session PWed

On signatures of sonic wavepackets in time-resolved x-ray diffractometry of metal single crystals absorbing pulse from ultrafast laser

Oleg Korovyanko, Merced College (United States); Oleksandra Korovyanko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

Copper (Cu), gold (Au) (111) crystals were illuminated with 120 fs pulses and probed by 600 fs X-ray pulses. Rocking curves were measured versus 267 nm (UV) pump- 0.154 nm (CuK?? probe delay time. Curve width broadening, peak diffracted intensity and angular shift were recorded for UV excitation intensities ranging 2-8 mJ/cm2 . Observed oscillations with time delay of shift, width and of peak intensity of rocking curves are correlated, and described by an acoustic pulse bouncing between crystal surfaces. In (111) Au, the acoustic pulse originates from the pump absorption layer, and its peak intensity drops by a factor of two as it wave reaches Au-substrate boundary. In Cu, correlated rocking curves dynamics are also observed. However, the rocking curve broadens faster than one can expect from a sonic wavepacket originating in the pump absorption layer. This effect is attributed to acoustic phonon generation outside of pump absorption layer, and is much stronger in Cu than in Au. Phonon generation in Cu is distributed throughout the whole bulk of crystal due to delocalization of mobile hot electrons diffusing from the pump absorption layer.

10102-51, Session 12

Decay of coherent acoustic phonons generated by femtosecond pulsed optical excitation and injected in a Wannier-Stark superlattice *(Invited Paper)*

Anthony J. Kent, Caroline L. Poyser, Andrey V. Akimov, William York, Mohamed Henini, Richard P. Campion, The Univ. of Nottingham (United Kingdom)

In the past decade, sound amplification by the stimulated emission of (acoustic phonon) radiation (saser) devices for generating coherent terahertz (THz) acoustic waves have been demonstrated [1 – 3]. The devices exploit the electron-phonon interactions in periodic semiconductor nanostructures known as superlattices (SLs) to amplify acoustic phonons. In addition, the particular acoustic properties of SLs can be exploited to make mirrors and cavities for THz phonons. Thus SLs can provide the two essential elements of a saser: the acoustic gain medium and the acoustic cavity.

In this presentation I will describe experimental studies of the THz phonon dynamics in a weakly-coupled GaAs/AlAs saser SL, which is DC electrically biased into the Wannier-Stark regime. Picoseconds-duration pulses of coherent THz acoustic phonons were generated using pump light pulses from a femtosecond laser and injected into the SL device. These phonon pulses seeded the saser cavity modes at about 220 and 440 GHz, which were amplified within the device. The phonons were detected using two methods: reflection of femtosecond probe light pulses, in a conventional pump-probe arrangement, and through the transient electrical response of the device itself.

When the DC bias conditions for saser were achieved in the device, the amplitude and lifetime of the seeded modes were both increased, analogous to the threshold and spectral line narrowing effects seen in laser devices.

[1] R P Beardsley et al., Phys. Rev. Lett. 104, 085501 (2010).

[2] W Maryam et al., Nature Communications 4:2184 (2013).

[3] K Shinokita et al., Phys. Rev. Lett. 116, 075504 (2016).

10102-52, Session 12

Ultrafast nanomechanics in vertical cavity surface-emitting lasers *(Invited Paper)*

Andrey V. Akimov, The Univ. of Nottingham (United Kingdom); Thomas Czerniuk, Dmitri R. Yakovlev, Manfred Bayer, Technische Univ. Dortmund (Germany)

The existence of both optical and sub-THz nanomechanical resonances in the same laser microcavity results in strong photon-phonon interaction, and may be explored for the ultrafast control of vertical lasers. In the talk the experiments involving the injection of picosecond strain pulses into optically and electrically pumped vertical lasers, and monitoring of the modulated output laser intensity will be discussed. The results of three recent experiments will be presented:

• In the experiments with an optically pumped quantum dot laser, an increase of the lasing output induced by strain pulses by two orders of magnitude has been observed on a picosecond time scale. Such strong and ultrafast increase is due to the inhomogeneous quantum dot ensemble with a spectral broadening much larger than the optical cavity mode width. Thus, the optical resonance required for lasing is achieved for a tiny dot fraction only while non-resonant dots store optical excitation for long time. The strain pulse brings “non-resonant” quantum dots into the resonance with the cavity mode and the stored energy releases almost simultaneously in a form of the intense laser pulses.

• Experiments with electrically pumped micropillar lasers show the modulation of the emission wavelength on the frequencies equal to the resonant GHz nanomechanical modes of the micropillar.

• Experiments with a quantum well vertical laser showed intensity modulation with the mechanical resonance frequencies (20-40 GHz) of the optomechanical nanoresonator.

10102-53, Session 12

Depth-dependent optical properties of H-implanted 4H-SiC and GaAs studied by coherent acoustic phonons

Andrey Baydin, Halina Krzyzanowska, Vanderbilt Univ. (United States); Munthala Dhanunjaya, S. V. S. Nageswara Rao, Univ. of Hyderabad (India); Jimmy L. Davidson, Vanderbilt Univ. (United States); Leonard C. Feldman, Rutgers, The State Univ. of New Jersey (United States); Norman H. Tolk, Vanderbilt Univ. (United States)

Silicon carbide (SiC) and gallium arsenide (GaAs) are semiconductors widely used in optoelectronics. SiC is a very promising material for new generation electronics operating at high power/high temperature devices and advanced optical applications such as room temperature electronics as well as quantum computing. GaAs is more often used to produce a material system in which a thin, bulk quality GaAs layer is monolithically integrated on a silicon substrate for perspective Si-on-chip application. Mentioned applications require the control of defects particularly those created by ion bombardment. In this work, we report modification of 4H-SiC optical constants and photoelastic coefficients of GaAs due to hydrogen implantation at low fluences (1014 - 1016 cm?2). Depth dependence of optical properties in H implanted 4H-SiC and GaAs is obtained from coherent acoustic phonon spectra. A comparison between indirect (4H-SiC) and direct (GaAs) band gap semiconductors shows the sensitivity of coherent acoustic phonon spectroscopy to different optical properties of both semiconductors; the changes in the complex refractive index of 4H-SiC and the changes in the photoelastic coefficients of GaAs arising from H implantation. These studies provide basic insight into the dependence of optical properties of both semiconductors on defect densities created by ion implantation, which is of relevance to the fabrication photonic and optoelectronic devices.

10102-54, Session 12

How thin should a vitreous silica layer be for boson peak measurement?

Tsung-Chi Hung, Yu-Ru Huang, National Taiwan Univ. (Taiwan); Jinn-Kong Sheu, National Cheng Kung Univ. (Taiwan); Chi-Kuang Sun, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan)

Amorphous materials, such as glasses, polymers, gels, or even bio-tissues, are an indispensable part of our lives. Unlike crystalline solids, amorphous materials exhibit some anomalous thermal properties that are still under debate. The reduced density of vibrational states versus sound frequency near 1THz disobeys the Debye model and shows a peak, usually termed the boson peak. This excess density of states is often related to a plateau in thermal conductivity and a maximum in the reduced heat capacity around 1-10 Kelvin. This boson peak is expected to provide extra acoustic attenuation for propagating acoustic waves with a frequency around 1THz. In this presentation, we discuss the optimal thickness of a vitreous silica layer in which the THz acoustic waves will propagate through to render the acoustic attenuation constant measurement. In this potential experiment, the thickness of the vitreous silica layer becomes a critical issue. It can't be too thick because the attenuation will be so high that the THz acoustic wave may be completely depleted; while it can't be too thin because the wavelength (several nanometers) of the THz acoustic wave can be much longer than the layer thickness and the resulted measurement accuracy will be compromised. In this study, by using femtosecond acoustics with a bandwidth over 1THz, we explore the sample thickness issue of this much-needed experiment. Results with different layer thickness will be presented and will be compared with the current direct or indirect measurement results.

10102-55, Session 12

Ultrafast carrier dynamics unravel role of surface ligands and metal domain size on the photocatalytic hydrogen evolution efficiency of Au-tipped CdS nanorods

Yuval Ben-Shahar, The Hebrew Univ. of Jerusalem (Israel); Ilka Kriegel, Istituto Italiano di Tecnologia (Italy); Francesco Scotognella, Politecnico di Milano (Italy); Nir Waiskopf, The Hebrew University of Jerusalem (Israel); Stefano Dal Conte, Luca Moretti, Giulio Cerullo, Politecnico di Milano (Italy); Eran Rabani, Tel Aviv Univ. (Israel) and Lawrence Berkeley National Lab. (United States); Uri Banin D.V.M., The Hebrew Univ. of Jerusalem (Israel)

Semiconductor-metal hybrid nanostructures are interesting materials for photocatalysis. Their tunable properties offer a highly controllable platform to design light-induced charge separation, a key to their function in photocatalytic water splitting. Hydrogen evolution quantum yields are influenced by factors as size, shape, material and morphology of the system, additionally the surface coating or the metal domain size play a dominant role.

In this paper we present a study on a well-defined model system of Au-tipped CdS nanorods. We use transient absorption spectroscopy to get insights into the charge carrier dynamics after photoexcitation of the bandgap of CdS nanorods. The study of charge transfer processes combined with the hydrogen evolution efficiency unravels the effects of surface coating and the gold tip size on the photocatalytic efficiency.1,2 Differences in efficiency with various surface ligands are primarily ascribed to the effects of surface passivation. Surface trapping of charge carriers is competing with effective charge separation, a prerequisite for photocatalysis, leading to the observed lower hydrogen production quantum yields. Interestingly, non-monotonic hydrogen evolution efficiency with size of the gold tip is observed, resulting in an optimal metal domain size for the most efficient photocatalysis. These results are explained by the size-dependent interplay of the metal domain charging and the relative band-alignments. Taken together our findings are of major importance for the potential application of hybrid nanoparticles as photocatalysts.

(1) Ben-Shahar, Y. et al. Nat. Commun. 2016, 7, 10413.

(2) Ben-Shahar, Y. et al. Small 2015, 11, 462–471.

10102-56, Session 13

Giant nonlinear optical activity of achiral origin in planar metasurfaces *(Invited Paper)*

Thomas Zentgraf, Univ. Paderborn (Germany); Shumei Chen, The Univ. of Birmingham (United Kingdom) and Hong Kong Baptist Univ. (Hong Kong, China); Franziska Zeuner, Univ. Paderborn (Germany); Martin Weismann, Univ. College London (United Kingdom); Bernhard Reineke, Univ. Paderborn (Germany); Guixin Li, Univ. Paderborn (Germany) and Univ. of Birmingham (United Kingdom); Ventsislav Kolev Valev, Univ. of Bath (United Kingdom); Kok Wai Cheah, Hong Kong Baptist Univ. (Hong Kong, China); Nicolae Coriolan Panoiu, Univ. College

London (United Kingdom); Shuang Zhang, The Univ. of Birmingham (United Kingdom)

Chiral plasmonic nanomaterials have been investigated for their selective interaction with circularly polarized light, which can enable, for instance, highly localized control of circularly polarized light emission. On the other hand, there has been a growing interest in the investigation of the nonlinear optical properties of plasmonic nanostructures due to the associated strong enhancements of electromagnetic fields and the capability to engineer the structural symmetry of their unit cell. Meanwhile several experiments demonstrate strong nonlinear optical circular dichroism of plasmonic nanostructures. However, the observed nonlinear optical circular dichroism in most experiments arises either from the chirality of 3D nanostructures, or from the extrinsic contribution in the case of 2D structures when the fundamental beam is incident at oblique angles. It should be pointed out that even seemingly 2D chiral materials, such as monolayers of chiral thin-film nanostructures are intrinsically 3D chiral. In such nanostructures, chirality arises from the presence of a substrate on one side of the thin-films.

Here, we show that 3D chiral structures are not necessary for introducing strong circular dichroism for harmonic generations. Specifically, we demonstrate giant nonlinear circular dichroism reaching nearly unity for both second harmonic and third harmonic generation on suitably designed ultrathin plasmonic metasurfaces containing Trisceli- and Gammadion-type plasmonic nanostructures. Our experimental results and the theoretical analysis show that the overwhelming contribution to this nonlinear circular dichroism is of achiral origin. The results shed new light on the origin of the nonlinear circular dichroism effect in achiral planar surfaces.

10102-57, Session 13

Wave mixing at the nanoscale: From plasmonic to hybrid structures *(Invited Paper)*

Maeliss Ethys de Corny, Nicolas Chauvet, Guillaume Laurent, Mathieu Jeannin, Aurelien Drezet, Serge Huant, Institut NÉEL (France); Thierry Gacoin, Ecole Polytechnique (France); Géraldine Dantelle, Gilles Nogues, Guillaume Bachelier, Institut NÉEL (France)

Scalability of optical devices is a major challenge for quantum optics and quantum cryptography fields. However, non-linear optical processes such as second harmonic generation (SHG) and parametric-down conversion become very inefficient when the active medium is reduced to the nanoscale. Enhancement strategies are therefore mandatory.

Here, we first investigate the role of plasmonic resonances in single aluminum nanostructures allowing doubly resonant and mode-matched conditions. We show that the SHG rate can be 36-fold enhanced compared to non-resonant structures. We further infer the origin of the nonlinearity by quantitatively comparing simulated and measured SHG maps obtained by scanning the antennas under a tightly focused beam.

The SHG response of a KTP nano-crystal and its modification by the proximity of a plasmonics antenna can then be confidently modeled. We show that the harmonic photon production yield is comparable for a bare nano-crystal and a doubly resonant aluminum antenna, despite the centro-symmetric nature of the latter. Combining the nonlinearity of the KTP crystal and the field enhancements provided by the plasmonic structure at both fundamental and harmonic frequency, we demonstrate that the SHG signal can be magnified by more than two orders of magnitude. The anticipated efficiency of the hybrid nonlinear plasmonic structures is compared to experiments performed at the single structure level, emphasizing the crucial role of the nanocrystal orientation.

10102-58, Session 13

Fano coil-type resonances: a plasmonic tool for the magnetic field manipulation

Simone Panaro, Remo Proietti Zaccaria, Andrea Toma, Istituto Italiano di Tecnologia (Italy)

Spintronics and spin-based technology rely on the ultra-fast unbalance of the electronic spin population in quite localized spatial regions. However, as a matter of fact, the low susceptibility of conventional materials at high frequencies strongly limits these phenomena, rendering the efficiency of magnetically active devices insufficient for application purposes. Among the possible strategies which can be envisaged, plasmonics offers a direct approach to increase the effect of local electronic unbalancing processes. By confining and enhancing free radiation in nm-size spatial regions, plasmonic nano-assemblies have demonstrated to support very intense electric and magnetic hot-spots. In particular, very recent studies have proven the fine control of magnetic fields in Fano resonance condition. The near-field-induced out-of-phase oscillation of localized surface plasmons has manifested itself with the arising of magnetic sub-diffractive hot-spots. Here, we show how this effect can be further boosted in the mid-infrared regime via the introduction of higher order plasmonic modes. The investigated system, namely Moon Trimer Resonator (MTR), combines the high efficiency of a strongly coupled nano-assembly in Fano interferential condition with the elevated tunability of the quadrupolar resonance supported by a moon-like geometry. The fine control of the apical gap in this unique nanostructure, characterizes a plasmonic device able to tune its resonance without any consequence on the magnetic hot-spot size, thus enabling an efficient squeezing in the infrared.

10102-59, Session 13

Near-infrared perovskite plasmon lasers with low threshold

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High-quality single-crystalline CH3NH3PbI3 nanowires were prepared on ITO/PEDOT: PSS substrates. SEM images show the typical nanowires present lengths about 4 - 8?m and widths around 300 – 400nm. EDS was performed on individual nanowires, which gives an I/Pb ratio of 2.76, as expected from the CH3NH3PbI3 stoichiometry. The clear crystal lattices from HRTEM image, together with the electron diffraction and Fourier transformed patterns indicate a good quality of the crystallization. The XRD pattern demonstrates a set of sharp peaks that can be assigned to tetragonal crystal structure without impurity phases. The PL peak is at around 777nm, and optical absorption spectra show a low concentration of in-gap defects.

The plasmonic lasers investigated herein consist of perovskite nanowires on a silver film with a 10 MgF2 spacer layer. The calculated mode distribution shows the nanowire mode is confined to an ultra-small mode size near the dielectric spacer layer, with sub-wavelength confinement in two dimensions perpendicular to the nanowire axis.

These nanowires were dry-transferred onto Ag/MgF2 substrates to form the hybrid plasmonic nanowire laser configuration. The emission spectra under varying pump power shows the laser has a low threshold of 112.9 MW cm-2/13.5 ?J cm-2. A blue shift of the laser wavelength with increasing pump is observed, which is characteristic of plasmonic laser action. The typical nonlinear kink in “S” shaped plot of the emitted laser intensities in accordance to pump power indicates a standard lasing signature. From the “s’’ shaped L-L curve, the ? factor is obtained to be 43%.

10102-60, Session 14

Optical tuning of electronic valleys *(Invited Paper)*

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Monolayer transition-metal dichalcogenides such as MoS2 and WS2 are prime examples of atomically thin semiconducting crystals that exhibit remarkable electronic and optical properties. They have a pair of valleys that can serve as a new electronic degree of freedom, and these valleys obey optical selection rules with circularly polarized light. Here, we discuss how ultrafast laser pulses can be used to tune their energy levels in a controllable valley-selective manner. The energy tunability is extremely large, comparable to what would be obtained using a hundred Tesla of magnetic field. We will also show that such valley tunability can be performed while we effectively manipulate the valley selection rules. Finally, we will explore the prospect of using this technique through photoemission spectroscopy to create a new phase of matter called a valley Floquet topological insulator.

10102-61, Session 14

High temporal resolution ultrafast electron diffraction applied to lattice dynamics of few-layer 2D materials *(Invited Paper)*

Christian Gerbig, Silvio Morgenstern, Marlene Adrian, Arne Senftleben, Thomas Baumert, Univ. Kassel (Germany)

Single crystals of graphite are highly anisotropic systems, with strong covalent bonds along one plane and weak interactions in the perpendicular stacking direction. Their structure gives rise to unique electronic properties but also to a strong non-adiabatic coupling between electrons and phonons.

Recently, electron-phonon coupling of optically excited graphite has been studied from the lattice perspective. Coherent optical phonons of the shearing mode have been observed by imaging the lattice vibrations through ultrafast electron diffraction (UED). The vibration exhibited different phases along different crystal directions.

Here, we discuss how this behaviour correlates with the polarization of the exciting light and the anisotropic electron-phonon coupling. Experiments were performed with our compact UED set-up with sub-100 fs temporal resolution. We measured the diffracted electron signal as a function of the time after optical excitation. Coherent phonons lead to oscillations of the diffraction signal. The shearing mode exhibits a clear anisotropy in momentum space. This anisotropy is traced back to the excitation mechanism of the phonons and hence to the polarization of the light field.

10102-62, Session 14

Optical properties of monolayer MoS2 exposed to helium ions

Julian Klein, Marcus Altzschner, Anna Nolinder, Jakob Wierzbowski, Florian Sigger, Ursula Wurstbauer, Alexander Holleitner, Jonathan J. Finley, Michael Kaniber, Walter Schottky Institut (Germany)

We present a spectroscopic study on mono- and few-layers of 2H stacked MoS2 and WSe2 which are exposed with helium ions. Distinct changes of the first-order Raman bands, additional defect luminescence and strong modification of the intrinsic valley spin relaxation properties are observed, shedding light on the effect of disorder on valley spin relaxation mechanisms.

We used a helium ion microscope to expose pristine MoS2 and WSe2 flakes exfoliated on SiO2/Si with helium ions, as a function of beam doses ranging from ~10^12 and ~10^16 ions/cm^2 and exposed areas of 4 x 4 μm^2. Exposed locations were investigated by Raman spectroscopy, low-temperature confocal micro-photoluminescence (μ-PL) and atomic force microscopy (AFM). The Raman signal in monolayer MoS2, for an increasing helium ion dose exhibits a clear broadening of both, first-order in-plane (E') and out-of-plane (A'1) phonon modes, accompanied by a redshift of the E' mode and a blueshift of the A'1 mode which can be well explained by a phonon confinement model [1]. Moreover, we observe distinct changes in the PL emission after treatment with helium ions, in particular additional strong defect luminescence arises 130 meV redshifted with respect to the A exciton in MoS2 . Quasi-resonant polarization resolved μ-PL measurements reveal a strong drop in the degree of circular polarization ?? for an increasing helium ion dose from ~85% to ~15%, indicative of a decrease of the valley spin relaxation time ??vs. We even observe values below the radiative recombination time ??0 of the A exciton for the lowest ??, which enables us to study the intrinsic valley spin relaxation mechanisms. Our results demonstrate the potential of helium ion microscopy applied to 2D layered materials for modifying intrinsic optical properties and fundamental understanding of disorder.

[1] Mignuzzi et al., PRB 91, 195411 (2015)

10102-63, Session 14

Electrically-driven GHz range ultrafast graphene light emitter

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Ultrafast electrically driven light emitter is a critical component in the development of the high bandwidth free-space and on-chip optical communications. Traditional semiconductor based light sources for integration to photonic platform have therefore been heavily studied over the past decades. However, there are still challenges such as absence of monolithic on-chip light sources with high bandwidth density, large-scale integration, low-cost, small foot print, and complementary metal-oxide-semiconductor (CMOS) technology compatibility. Here, we demonstrate the first electrically driven ultrafast graphene light emitter that operate up to 10 GHz bandwidth and broadband range (400 ~ 1600 nm), which are possible due to the strong coupling of charge carriers in graphene and surface optical phonons in hBN allow the ultrafast energy and heat transfer. In addition, incorporation of atomically thin hexagonal boron nitride (hBN) encapsulation layers enable the stable and practical high performance even under the ambient condition. Therefore, electrically driven ultrafast graphene light emitters paves the way towards the realization of ultrahigh bandwidth density photonic integrated circuits and efficient optical communications networks.

10102-67, Session 14

High harmonic generation in graphene: Temporal and spectral properties.

Luis Plaja, Óscar Zurrón, José Manuel Iglesias, María Jesús Martín, Raul Rengel, Univ. de Salamanca (Spain)

Graphene has been recently reported to have a damage threshold high enough to allow for the interaction with ultrashort pulses of strong laser fields. In similar situations, atoms and solids are known to emit high-order harmonics in the form of phase locked frequency combs. From the temporal viewpoint, these combs correspond to trains of attosecond pulses. It is natural to explore if this situation can have an analogue in 2D materials, and to what extend the laser pulse is able to induce the non-perturbative dynamics that gives rise to this phenomenology.

In this work we develop the theory for the computation of high-harmonics in Graphene. Our approach is not based in the Strong-Field Approximation, used for atoms and molecular targets, that assumes electrons excited to the conduction band as free particles. Instead, we perform the exact numerical integration in the Brillouin zone (BZ), therefore preserving the details of the electron dispersion when promoted to the conduction band. Diffusion is taken into account phenomenologically with parameters extracted from the numerical solution of transport equations by means of a stochastical Monte Carlo model".

In this way, we are able to analyze the role of intra-band and inter-band transitions in the harmonic spectrum. Our model predicts a rich harmonic content, for intensities lower than those employed in atomic systems. We also analyze the contribution to the harmonic spectrum of different regions of the BZ, and the dominant role of resonant transitions. We also show results of the time-frequency analysis of the harmonic spectra, and the temporal characteristics of the harmonic emission.

10103-1, Session 1

Terahertz source-receiver technologies: biomedical imaging applications *(Invited Paper)*

Robert H. Giles, Jillian P. Martin, Univ. of Massachusetts Lowell (United States); Pallavi Doradla, Wellman Ctr. for Photomedicine (United States); Cecil S. Joseph, Univ. of Massachusetts Lowell (United States)

Since 1982, the researchers at the University of Massachusetts Lowell have been developing solid-state and laser-based terahertz sources with high-sensitivity incoherent and coherent receivers for high-resolution full-polarimetric imaging techniques. With the goal to develop and apply the technology in the frequency range of 100 GHz to 3 THz, UML researchers have engineered and constructed measurement systems to investigate an ever-growing number of applications in the areas of medicine, materials science, physical scale imaging and remote-sensing where atmospheric transmission is adequate. A summary of research initiatives and findings of the BTTC will be presented along with the foundation of material characterization methods and polarimetric system design considerations for biomedical applications.

10103-2, Session 1

Active moleculization of terahertz meta-atoms

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In recent years, active tuning of terahertz metamaterials have been numerous interests in worldwide researchers for developing diverse terahertz applications such as active filters, sensors, and imaging systems. Especially, electrical control of metamaterials is considered as a highly motivated technique to realize the active metamaterial devices, but has suffered from the unsatisfactory tuning ranges and the limited design methods. In this paper, we propose electrochemically reconfigurable terahertz meta-atoms by using the graphene bridges to realize broadband tunability and switchability of the active metamaterials. The graphene bridges were aligned to inter-connect the adjacent meta-atoms along the specific incident polarization and the ionic gel was coated as the gating material to control the graphene conductivity which could manipulate the electrical connection between adjacent meta-atoms. This inter-atomic bonding of meta-atoms, referred as 'moleculization' of meta-atoms, was designed and simulated with various numbers of inter-connecting graphene bridges and fabricated on the flexible 5-um-thick polyimide substrate. With numerical simulation and experimental results, we confirm that the proposed moleculization systems successfully exhibit broad tuning range of their resonance properties and high switching ratio at the specific frequencies. Finally, our meta-atom moleculization system is introduced for the first time to provide one of the prime design methods for active metamaterial devices, and is expected to eventually realize the custom-designed tunable and switchable metamaterials.

10103-3, Session 1

Plasmonics-enhanced large-area terahertz detectors

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One of the main limitations for realizing high-performance time-domain terahertz imaging and spectroscopy systems is the low responsivity and narrow bandwidth of the existing pulsed terahertz detectors. In this work, we present a high-responsivity and broadband large-area terahertz detector that incorporates a two-dimensional array of plasmonic nanoantennas fabricated on a low-temperature-grown GaAs substrate. By using a large-area device architecture, large optical spot sizes can be used, mitigating the carrier screening effect at high optical pump powers. Using a large-area device architecture also makes the device less sensitive to changes in optical and terahertz alignment. The two-dimensional array of plasmonic nanoantennas is designed to offer a broad terahertz detection bandwidth. It is also designed to enhance optical absorption in close proximity to the nanoantennas by exciting surface plasmon waves. This allows drifting a large portion of photo-generated electrons and holes to the nanoantennas in presence of an incident terahertz pulse, offering high responsivity levels. We experimentally demonstrate detection of terahertz pulses with more than 5 THz bandwidth with high responsivity and signal-to-noise ratio levels exceeding that of electro-optic detectors. Such terahertz detectors would play a critical role in realization of the next generation time-domain terahertz imaging and spectroscopy systems.

10103-4, Session 1

High-sensitivity intensity correlation measurements for photon statistics at terahertz frequencies

Ileana-Cristina Benea-Chelmus, Giacomo Scalari, Jérôme Faist, ETH Zürich (Switzerland)

Recently, intensity correlation measurements have been reported for the first time for the Terahertz frequency range, where a time-domain version of a Hanbury Brown Twiss setup based on electro-optic sampling was employed. With this technique, the photon statistics of a Terahertz Quantum Cascade Laser during its transition to laser action were measured.

The technique, which has inherently a very short temporal resolution, limited only by the probing near-infrared pulse to few hundreds of femtoseconds, is particularly adapted for future studies of ultra-broadband Terahertz radiation. However, reaching the interesting regime of single photon detection requires a substantial increase in sensitivity.

In this work we present our recent efforts into increasing the sensitivity of electro-optic sampling, by cooling down the detection crystal to cryogenic temperatures, and by exploring the usability of highly non-linear organic molecules with non-linear coefficients as high as 100 pm/V in an on-chip scheme for Terahertz detection.

10103-5, Session 2

Generations of linear frequency modulation continuous waves

Tianxin Yang, Da Xing, Zhaoyu Lu, Chunfeng Ge, Tianjin Univ. (China)

An external modulation technique for the generation of optical linearly chirped frequency continuous waves is proposed and experimentally demonstrated. The signals are produced by modulating a continuous wave (CW) laser using an extra-cavity single sideband (SSB) modulator that is driven by a frequency linearly chirped electrical signal from an arbitrary wave generator (AWG).The jitter rates of the frequency linearly chirped optical signals generated herein are always less than 10 % even when the chirp rates are changed over 3 orders of magnitude from 5 GHz/ms to 2.5 THz/ms. The lowest jitter rate of 5.69 % and the best linearity of 0.9990 are obtained from the experimental measurements reported in this paper.

10103-6, Session 2

Simplest passive millimeter-wave discriminator for the finding of objects

Alexander G. Denisov, Harbin Institute of Technology (China)

Radiometric discriminator is the simplest device for comparing the radiometric brightness temperature of two following spots of antenna beam on the observed remote scene. In this case, the real signal from discriminator can be similar to the radar imaging in form of the bright points based on the difference between the metal object and the background of an absorbing or semi-absorbing environment. To realize the function of finding objects, the scanning antenna is symmetrically decided into two parts. This signal arises only when the two parts generate different levels of brightness temperatures because of a target captured in alternative pixel scanning along the observed scene. In this paper, the device named discriminator is proposed, and the operating principle and possible application is introduced for the object with Stealth coating.

10103-7, Session 2

Sparse multistatic line-array-based 3D terahertz imaging system with real-time capability for industrial applications

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Terahertz imaging solutions are of high interest for many industrial non-destructive testing applications. This typically poses high demands on real-time signal acquisition and processing. For applications which require large field-of-views with cross-ranges from several tenths to a few meters, sparse multistatic line arrays in combination with digital beam forming techniques provide an optimal imaging solution, which overcome limitations such as the need for mechanical scanning with single quasi-optical sensors or the trade-off between field-of-view and image resolution posed by focal plane arrays. Furthermore the possibility to obtain depth information by frequency modulation techniques allows for 3D feature localization. We developed a 3D imaging system using a sparse multistatic line array, which operates in the W-band with a modulation bandwidth of 35 GHz. The array consists of only 12 transmitters and 12 receivers with an effective aperture of 40 cm. In order to generate a 2D sampling aperture the line array is used in combination with a conveyor for synthetic aperture focusing along the feed motion. For real-time 3D image reconstruction we take advantage of the fast factorized back-projection method or alternatively of an especially developed range migration algorithm. The algorithms have been implemented for their application on general purpose graphic processing units. The key features of the novel system are the real-time terahertz image reconstruction with a dynamic range of up to 40 dB at feed velocities of several 10 cm/s and a spatial resolution around 4 mm.

10103-8, Session 2

A low noise readout integrated circuit for Nb5N6 microbolometer array detector

Zhou Jiang, Chao Wan, Peng Xiao, Chengtao Jiang, Xuecou Tu, Xiaoqing Jia, Lin Kang, Jian Chen, Pei Heng Wu, Nanjing Univ. (China)

We present a readout circuit for 1 ? 64 Nb5N6 microbolometer array detector for terahertz imaging. The intrinsic average responsivity of the detectors in the array is 650 V/W, and the corresponding noise equivalent power (NEP) is 17 pW/√Hz. Due to the low noise of the detector, we design a low noise readout circuit with 64 channels. The readout amplifier is fabricated under CMOS process with 0.18 ?m design rule, which has built-in bias and adjustable numerical-controlled output current. Differential structure is used for each pixel to boost capacity of resisting disturbance. A multiplexer is followed after the amplifier. It is shown that the circuit achieves an equivalent input power of 10.7 nV/√Hz at 10 KHz and power dissipation of less than 6 mW. The performance of this readout circuit nearly fulfills the requirements for THz array detector.

The array detector was preliminary used for THz source imaging, and more imaging experiments are being done. The experiments for other object imaging by using this array detector have been done, and the results are demonstrated in the literature. From the imaging results, we can learn that this readout circuit is proper for the detector, which indicates a good way to develop efficient and low-cost THz imaging system.

10103-9, Session 2

Conception and realization of a semiconductor based 240GHz full 3D MIMO imaging system

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Multiple-input multiple-output (MIMO) imaging systems in the terahertz (THz) frequency range have a high potential in the field of non-destructive testing (NDT). With such systems it is possible to detect defects in composite materials, for example cracks or delaminations in fiber composites. To investigate mass-produced products it is necessary to study the objects directly on a conveyer without affecting the production time. In this work we present the conception and realization of a 3D MIMO imaging system for in-line investigation of composite materials.

To achieve a lateral resolution of 1mm, in order to detect such small defects in composite materials with a moderate number of elements, precise sensor design is crucial. In our approach we use the effective aperture concept. The designed sparse array consists of 32 transmitters and 30 receivers based on planar semiconductor components. High range resolution is achieved by an operating frequency between 220GHz and 260GHz in a stepped frequency continuous wave (SFCW) setup.

A matched filter approach is used to simulate the reconstructed 3D image through the array. This allows the evaluation of the designed array geometry in regard of resolution and side lobe level. In contrast to earlier demonstrations, in which synthetic reconstruction is only performed in a

2D plane, an optics-free full 3D reconstruction has been implemented in our concept. Based on this simulation we designed an array geometry that enables to resolve objects with a resolution smaller than 1mm and moderate side lobe level.

10103-10, Session 3

Material anisotropy effects in dielectric THz metamaterials

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Terahertz resonators made of high-permittivity dielectric materials squeeze terahertz electromagnetic energy to deeply subwavelength volumes. This allows for packing such resonators in an array with a subwavelength pitch, creating a metamaterial or a metasurface. Intrinsic material anisotropy splits the magnetic and electric resonant Mie modes, sustained by dielectric resonators, into orthogonal modes with different resonance frequencies.

Our near-field terahertz experiments confirm such splitting in strongly anisotropic mono-crystalline titanium dioxide micro-spheres. We used near-field time-domain spectroscopy to detect and characterise the intrinsic properties of narrow Mie resonances sustained by such dielectric resonators with sizes comparable to one-tenths of the corresponding free-space terahertz wavelengths. We showed that depending on the mutual orientation of the excitation field polarisation plane and the main crystallographic axis of the anisotropic material, one can excite either one or both of the ordinary and the extraordinary Mie modes. Analysing the spectral positions of the split modes, we observed strong terahertz birefringence in mono-crystalline titanium dioxide. We applied simple Fano formalism to extract the intrinsic properties of strongly anisotropic dielectric terahertz resonators from their measured near-field terahertz spectra.

Ensembles of titanium dioxide micro-resonators can form meta-atoms for all-dielectric terahertz metamaterials with unusual electromagnetic responses; at the same time, the geometry of the meta-atom's components stays simple. We show that material anisotropy provides an additional degree of freedom in advanced light manipulation in complex resonators, metamaterials and metasurfaces at terahertz frequencies.

10103-11, Session 3

Temperature evolution of topological surface states in bismuth selenide thin films studied using terahertz spectroscopy

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The unique properties of TIs with insulating bulk and conducting surface states have been attributed to the time reversal symmetry and the presence of strong spin orbit interaction. Terahertz (THz) spectroscopy is an optical technique, free of contacts to probe the low-energy excitations in strongly correlated electron gases. We combine THz spectroscopy with high quality TI films grown by MBE to understand the evolution of topological surface states of the Bi2Se3 film, grown on a sapphire substrate. In this work, we used THz time-domain spectroscopy and measured the optical conductance of Bi2Se3, revealing a 1/ T dependence, where T is the lattice temperature. We measure the THz conductance of thin film (20 QL) Bi2Se3 as 5e2/h at 4K. This is indicative of a surface like response only visible at smaller lattice temperature. THz conductance shows a Drude like response, superimposed with features from quantum well states resulting from band bending near surface, possibly due to selenium vacancies. The THz conductance reveals a characteristic feature at ~ 2.1 THz representing A1g phonon mode, which is weakly visible at 4K but becomes more prominent with increasing temperature, due to increased interaction with the bulk states. The momentum relaxation time of surface electrons was calculated independently of conductance, as 11 picoseconds (ps) at 4 K. Further, the charge carrier concentration was deduced to be 1.2 ?1013 cm-2. In conclusion this work not only provides fundamental insight into the topological surface state response of Bi2Se3, but also demonstrates the capability to detect and manipulate them.

10103-12, Session 3

Advanced temporal characterization of free electron laser pulses at European XFEL by THz photoelectron spectroscopy

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The European X-ray Free Electron Laser facility (XFEL.EU), which will become operational in 2016, shows extraordinary features with its extremely high number of light pulses per second (27000 p/s) and extremely high average brilliance. So far, characterizing the temporal properties of the free electron laser pulses in a single shot basis is important and challenging.

In this paper, we report on the concept and recent progress concerning high repetition rate temporal diagnostics by THz photoelectron spectroscopy. A single-cycle THz pulse, generated by tilted pulse-front excitation in a Lithium Niobate (LN) crystal, with central frequency of 0.65 THz and field strength of ~200 kV/cm has been applied, and future upgrade and results pumped by a MHz excitation pulse will be demonstrated. The measurement of the self-sustained THz dressed photoelectron spectrogram gives the direct information of the relative time delay between x-ray FEL and THz field as well as the pulse structure of the x-ray FEL, ranging from XUV to hard X-ray region. Meanwhile, we propose different candidate photoemission lines for different photon energies and pulse durations from 10 to 100 fs, and a comprehensive simulation based on the design parameter of XFEL.EU has been demonstrated, together with an estimation of the temporal resolution of the mentioned method.

Our results present here serve as a reference and instruction to FEL facilities that deliver x-ray photons with variable photon energy, pulse duration and repetition rate.

10103-13, Session 3

InGaAs Schottky barrier diode array detectors integrated with broadband antenna

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Terahertz (THz) waves have been actively studied for the applications of astronomy, communications, analytical science and bio-technologies due to their low energy and high frequency. For example, THz systems can carry more information with faster rates than GHz systems. Besides, THz waves can be applied to imaging, sensing, and spectroscopy. Furthermore, THz waves can be used for non-destructive and non-harmful tomography of living objects. In this reasons, Schottky barrier diodes (SBD) have been widely used as a THz detector for their ultrafast carrier transport, high responsivity, high sensitivity, and excellent noise equivalent power. Furthermore, SBD detectors envisage developing THz applications at low cost, excellent capability, and high yield. Since the major concerns

in the THz detectors for THz imaging systems are the realizations of the real-time image acquisitions via a reduced acquisition time, rather than the conventional raster scans that obtains an image by pixel-by-pixel acquisitions, a line-scan based systems utilizes an array detector with an 1 ? n SBD array is preferable.

In this study, we fabricated the InGaAs based SBD array detectors with broadband antennas of log-spiral and square-spiral patterns. To optimize leakage current and ideality factor, the dependence to the doping levels of ohmic and Schottky layers have been investigated. In addition, the dependence to the capacitance and resistance to anode size are also examined as well. As a consequence, the real-time THz imaging with our InGaAs SBD array detector have been successfully obtained.

10103-14, Session 3

<012>-cut chalcopyrite ZnGeP2 as a high-bandwidth terahertz electro-optic detection crystal

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The electro-optic (EO) detection capabilities of a <012>-cut chalcopyrite ZnGeP2 (ZGP) crystal, having a thickness of 1080 μm, are examined in the terahertz (THz) frequency regime. The ZGP crystal is used to detect a THz pulse emitted from a GaAs photoconductive antenna (PCA), which is compared to the EO signals measured using a 500 μm thick ZnSe crystal, as well as a 100 μm thick ZnTe crystal. Interestingly, both the ZGP and ZnTe crystals are able to detect all frequencies emitted from the GaAs PCA, despite the fact that ZGP is >10 times thicker than the ZnTe, while the ZnSe crystal is only able to detect approximately half of the emitted frequency components. These results suggest that ZGP exhibits excellent phase matching between the optical probe and THz pulses. The complex EO response function is implemented to quantify the phase matching characteristics of ZGP, ZnTe, ZnSe, and GaP. Phase matching for a 1080 μm thick ZGP crystal yields a detection bandwidth 1.3 times greater than ZnTe, and 4.8 times greater than ZnSe and GaP. As such, ZGP has promising applications in THz time-domain spectroscopy. The complex refractive index of ZGP is obtained at frequencies between 0.1-3.8 THz via transmission measurements. ZGP is shown to exhibit low THz losses (extinction coefficient ranges between 0.002 and 0.018) and dispersion (refractive index varies between 3.35 and 3.45) over this frequency range. Additionally, phonon-polariton effects do no appear in the measured data, suggesting that these effects are too weak to perturb the THz pulse.

10103-15, Session 3

Strong coupling of THz surface plasmon polaritons to complementary metasurfaces

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We study the transmission of complementary THz split ring resonator (cSRR) arrays with THz time domain spectroscopy. Utilizing complementary THz metasurfaces and, varying the inter meta-atom separation, a regime of resonant coupling to surface plasmon polaritons (SPPs) is entered. The effective medium condition valid for the direct metasurface is not applicable anymore in the complementary case because of the high THz dielectric constant of gold. We observe a normalized strong coupling of 3.5% to the lattice SPP mode when tuned into resonance with the LC-mode of the cSRR at a frequency of 1.07 THz. The lattice constant is varied from 40 um to 160 um. Finite element simulations with CST MWS show the characteristic field distribution of the two modes and the intermixing of the LC-mode with the SPP-mode very clearly. Analytical modeling with a simple two oscillator model well describes the coupling. An effective relative permittivity of 11.6 for the coupled system was extracted. For broader linewidths, an apparent modulation of the effective Quality-factor can be observed which is of crucial importance for designing metasurfaces for applications. Measurements of the broader lambda/2 mode in orthogonal excitation direction reveal instead a Fano-like interaction. Rectangular array configuration reveal the excitation direction of the SPP modes being along the polarization of the exciting THz pulse. We demonstrate that the understanding of the SPP modes is fundamental for research and applications in which the metasurface has to be designed for special needs.

10103-16, Session 4

Picosecond-pulse generation over 10-GHz repetition rate based on a coupled optoelectronic oscillator

Wenlong Tai, Zhaoying Wang, Dongfang Jia, Chunfeng Ge, Tianxin Yang, Tianjin Univ. (China)

There has been a requirement for optical pulse sources which have high repetition rates over 10 GHz and the pulsewidth of a few picoseconds simultaneously in the advanced optical communication and optical signal processing systems. It can be found in many research reports that the optical pulse trains at high repetition rate over 10 GHz are generated by various active harmonic mode-locked lasers. The typical pulsewidths are normally between 10 and 20 ps. This is because the transmission curves of the LN modulators are more smooth when the applied electrical signals are changing sinusoidally. On the other hand, there is no optoelectronic feedback mechanism in a pure active harmonic mode-locked laser therefore the noise and jitters in radio frequency (RF) generators cannot be suppressed effectively. However, in an optoelectronic oscillator short optical pulses can be generated without need of an RF generator provided that a narrow bandwidth electric filter at RF range is used. In this work an electroabsorption modulator (EAM) is used in a coupled optoelectronic oscillator to replace the conventional lithium niobate (LN) electro-optic modulators. The pulsewidths are reduced by one order of magnitude down to a few picoseconds due to the sharp nonlinear modulation effects in EAMs comparing the LN-modulator-based system. In addition, the stability of optical pulse train is improved by 10 dB comparing with the active harmonic mode-locked lasers.

10103-17, Session 4

Ultra-compact electromagnetic wave sensor featuring electro-optics polymer infiltrated one-dimensional photonic-crystal-slotted waveguide

Chi-Jui Chung, Zeyu Pan, Rui Wang, The Univ. of Texas at Austin (United States); Xiaochuan Xu, Harish Subbaraman, Omega Optics, Inc. (United States); Ray T. Chen, The Univ. of Texas at Austin (United States)

An ultra-compact Electro-Magnetic (EM) Wave Sensor working at 14GHz is designed and demonstrated experimentally. The sensor is based on electro-optics (EO) modulation and therefore has several important advantages over conventional electrical RF sensors including compact size and immunity to electromagnetic interference (EMI). The proposed sensor contains a set of bowtie antenna and a Mach-Zehnder interferometer (MZI) structure with one arm of slow-light enhanced EO polymer infiltrated one dimensional (1D) photonic crystal slotted waveguide and the other arm of silicon strip waveguide with tooth. To minimize the RC delay as well as the electrical connection between the two bowtie antenna, the innovative silicon tooth design are applied for both arms of the MZI respectively so

that the device can be operated at 14Ghz. The bowtie antenna concentrates electrical field of the impinging wireless EM wave at its designed frequency of 14Ghz and applies it onto the EO polymer filled slot for modulating phase of the guided optical wave. By combining the effect of strong slow light effect of the slotted PCW, high field enhancement of the bowtie antenna, and also large EO coefficient of the EO polymer(r33=135pm/V), the device is only 4.6mmX4.8mm in size with active region of 300?m and has minimum detectable electromagnetic power density as low as 27 mW/m2.

10103-18, Session 4

77-GHz radar for first responders

Lester H. Kosowsky, L.H. Kosowsky and Associates, Inc. (United States); Alan D. Aronoff, L. H. Kosowsky & Associates, Inc. (United States) and L.H. Kosowsky and Associates, Inc. (United States); Ralph Ferraro, Stephen Alland, L.H. Kosowsky and Associates, Inc. (United States); Eitan Fleischman, L.H. Kosowsky and Associates, Inc. (United States) and L. H. Kosowsky & Associates, Inc. (United States)

First responders have the dangerous task of responding to emergency situations in firefighting scenarios involving homes and offices. The importance of this radar is its ability to see through walls and into adjacent areas to provide the first responder with information to assess the status of a building fire, its occupants, and to supplement his thermal camera which is obstructed by the wall. For the firefighter looking into an adjacent room containing unknown objects including humans, the challenge is to recognize what is in that room, the configuration of the room, and potential escape routes. We have just concluded a series of experiments to illustrate the performance of 77GHz radar in buildings. The experiments utilized the Delphi Automotive radar as the mm wave sensor and included display software developed by L. H. Kosowsky and Associates. The system has demonstrated the capability of seeing through walls consisting of sheetrock separated by two by four pieces of wood. It has demonstrated the ability to see into the adjacent room and to display the existence of persons and furniture Based on published data, the radar will performs well in a smoke, haze, and/or fog environment.

10103-19, Session 4

Terahertz wireless interconnection based on InP-related devices

Eui Su Lee, Hyun-Soo Kim, Jeong-Woo Park, Dong Woo Park, Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of)

Recently, a wide interest has been gathered in using terahertz (THz) waves as the carrier waves for the next generation of broadband wireless communications. Upon this objective, the photonics technologies are very attractive for their usefulness in signal generations, modulations and detections with enhanced bandwidth and data rates, and the readiness in combining to the existing fiber-optic or wireless networks. In this paper, as a preliminary step toward the THz wireless communications, a THz wireless interconnection system with a broadband antenna-integrated uni-traveling-carrier photodiode (UTC-PD) and a Shottky-barrier diode (SBD) module will be presented. In our system, optical beating signals are generated and digitally modulated by the optical intensity modulator driven by a pulse pattern generator (PPG). As the receiver a SBD and an IF filter followed by a low-noise preamplifier and a limiting amplifier was used. With a 6-mA photocurrent of the UTC-PD which corresponds to the transmitter output power of about 30 ?W at 280 GHz, an error-free (BER<10-9) transmission has been achieved at 2.5 Gbit/s which is limited by a limiting amplifier. With this system, a 1.485-Gbit/s video signal with a high-definition serial digital interface format was successfully transmitted over a wireless link.

10103-20, Session 4

Field-trial demonstration of an extended-reach GPON-supporting 60-GHz indoor wireless access

Giannis Giannoulis, Nektarios Moraitis, Nikolaos Argyris, National Technical Univ. of Athens (Greece); Stefanos Dris, National Technical Univ. of Athens (Greece) and VPIphotonics GmbH (Germany); Christina Lessi, Stamatis Perdikouris, Hellenic Telecommunications Organization S.A. (Greece); Lydia Kostikidou, Dimitrios Apostolopoulos, Christos Spatharakis, National Technical Univ. of Athens (Greece); Ioanna Papafili, George Agapiou, Hellenic Telecommunications Organization S.A. (Greece); Athanasios Panagopoulos, Hercules Avramopoulos, National Technical Univ. of Athens (Greece)

The 5G era is nearly upon us, and poses a number of challenges for system designers; one important question is how the (soon to be standardized) mmWave bands of wireless mobile access can coexist harmoniously with optical links in fixed telecom networks. To this end, we present a Radio-over-Fiber (RoF) backhauling concept, interfaced to a 60 GHz indoor femto-cell via a field-installed optical fiber link. We successfully demonstrate generation of a RoF signal up to 1 Gb/s and transmit it optically over 43 km of deployed Single Mode Fiber (SMF), as well as investigate the performance of the 60-GHz access link as a function of distance. The optical link introduces negligible degradation, contrasting the effect of multipath fading in the 60-GHz wireless channel; the latter requires adaptive equalization using offline DSP. The proposed scheme is further validated by demonstration of a 60-GHz Remote Antenna Unit (RAU) concept, handling real traffic from commercial Gigabit Passive Optical Network (GPON) equipment. Proper RAU operation at 1.25 Gb/s is achieved, accommodating true data packets from a Media Converter emitting at 1310 nm through an in-building fiber link. System performance is confirmed through Bit Error Rate (BER) and Error Vector Magnitude (EVM) measurements. EVMs of ~11 and 19% are achieved with BPSK signals, for distances of 1 and 2 m respectively. As standardization of mmWave technologies moves from 5G testbeds to field-trial prototypes, successful demonstration of such 60-GHz wireless access scenarios over a telecom operator's commercial fiber infrastructure is all the more relevant.

10103-21, Session 4

Radiation patterns of multimode feed-horn-coupled bolometers for FAR-IR space applications

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A multimode horn differs from a single mode horn in that it has a larger sized waveguide feeding it. Multimode horns can therefore be utilized as high efficiency feeds for bolometric detectors, providing increased throughput and sensitivity over single mode feeds, while also ensuring good control of the beam pattern characteristics.

Although a cavity mounted bolometer can be modelled as a perfect black body radiator (using reciprocity in order to calculate beam patterns),

nevertheless, this is an approximation. In this paper we present how this approach can be improved to actually include the cavity coupled bolometer, now modelled as a thin absorbing film. Generally, this is a big challenge for finite element software, in that the structures are typically electrically large. Therefore, the radiation pattern of multi-mode horns can be more efficiently simulated using mode matching, typically with smooth-walled waveguide modes as the basis and computing an overall scattering matrix for the horn-waveguide-cavity system. Appropriate reflection and transmission matrices (S22 and S21) have to be determined for the cavity using the natural eigenfields of the bolometer cavity system.

Another issue on the optical efficiency of the detectors is the presence of any free space gaps, through which power can escape.

We will show how the approach can be applied to proposed terahertz systems, such as SPICA-SAFARI and also discuss how improvements to the predicted beam patterns on the sky for the HFI 857GHz channel on Planck can be made.

10103-22, Session 5

The three functions of terahertz technologies: an industrial perspective

Clémentine Bouyé, Sarah Taoudi, Jacques Cochard, Benoît d'Humières, TEMATYS (France)

For their ability to be transmitted by materials opaque in the visible and IR ranges (clothes, plastic, ...), for being non-ionizing, for providing sub-mm resolution imaging, for the specific signatures of numerous materials, Terahertz waves - ranging from 200 GHz to 10 THz - have been raising the interest of industrials for about fifteen years.

This study focuses on the penetration of THz technologies into the industrial applications driving the THz market growth at short and long term: Non Destructive testing (NDT), Defense and Security, Biomedical. For 15 years, Terahertz technologies have been continuously tested on a wide variety of applications. Thanks to these ongoing feasibility studies, manufacturers and end-users gained a deeper knowledge about the abilities and the limitations of the different Terahertz systems (Time-Domain spectroscopy, Frequency-Domain spectroscopy, Time-Domain reflectometry, etc). The demand from end-users is more qualified and is segmented as follows:

1. Detection of objects and defects on large areas

2. Thickness measurement on large areas

3. Chemical and Structural characterization of small objects and defects on small areas (2D) or volumes (3D)

Each of these 3 functions leads to a specific family of THz systems with distinct requirements in terms of performance and cost:

1. Detection: cheap and compact imaging systems.

2. Thickness measurement: cost-effective and high speed systems.

3. Characterization: high resolution, high reliability and real-time sensing systems.

This article will present the existing and incoming THz systems and components addressing each function. Terahertz technologies are currently finding their place on the market, outside research and scientific applications. The objective of this article is to identify the industrial applications where THz techniques will be adopted and to provide market growth perspectives.

10103-23, Session 5

Towards the industrialization of THz technology: the case of quality control of paper during production *(Keynote Presentation)*

J. L. M. van Mechelen, Hannes Merbold, Deran J. H. C. Maas, ABB Corporate Research (Switzerland)

The growing maturity of THz technology is paving the road towards industrial applications. One field where the technology could be used is quality control of automatized processes, such as in the coating and paper industry. Yet the process industry already successfully employs optical sensors and techniques. Therefore, a key question to answer is how THz technology can differentiate and create additional value that justifies its current price tag.[1]

Within this context, paper is an ostensibly promising material for THz applications. In order to evaluate its potential, we carried out a comprehensive study on a large variety of paper sheets in a realistic industrial environment. We employed a material analysis approach based on a stratified dispersive model, an appropriate measurement configuration and a time-domain fitting procedure, which together allow for high precision material parameter determination.[2] The main focus of the work related to the most business relevant parameters, the weight per surface area and the thickness. I will discuss our approach to sense these parameters in the light of the challenge that weight and electromagnetic radiation are not physically related, and thickness of a compressed sheet of fibers is not very well defined. Eventually, I give a paramount view on the maturity of THz technology for applications and the most prosperous direction for a successful short-term integration.

[1] D. van Mechelen, Optics & Photonics News 11, 16 (2015).

[2] J.L.M. van Mechelen, A.B. Kuzmenko, H. Merbold, Optics Letters 39, 3853 (2014).

10103-24, Session 5

Using terahertz-pulsed imaging (TPI) to study osmotic tablets *(Invited Paper)*

Brian Regler, Donna Carroll, Merck & Co., Inc. (United States); Alessia Portieri, TeraView Ltd. (United Kingdom); Zach Dance, Jim DiNunzio, Gary Chia, Jerry Klinzing, Lee Dowden, Gerard Bredael, David Harris, Merck & Co., Inc. (United States); Philip F. Taday, TeraView Ltd. (United Kingdom)

In this talk we will describe the application of terahertz pulsed imaging for measuring structural features like film coat thickness to better understand the push-pull mechanism of osmotic tablets. These tablets are in development to control the release of an active pharmaceutical compound by coating a bilayer tablet with a semipermeable membrane. One layer of the tablet contains an osmogen that serves as an engine for water flux into the tablet. Swelling of the internal tablet core drives the discharge of active through a port in the apex of the tablet's cap. The rate of release is controlled by many factors, with the thickness of the semipermeable membrane being the primary factor. In the study reported here, terahertz imaging was used to measure the semipermeable membrane coating thickness of 36 tablets from three (3) different development batches. The impact of coating thickness on the active ingredient release rate was measured using USP II dissolution apparatus. This data was analysed using chemometrics to develop a predictive model of release rate as a function of coating thickness.

10103-25, Session 5

Thickness determination of wet coatings using self-calibration method

Frank Ellrich, Jens Klier, Stefan Weber, Joachim Jonuscheit, Georg von Freymann, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

The correct determination of coatings in thickness is still a challenge in scientific as well as industrial applications. Finding the optimum method for

thickness measurements depends on several requirements, e.g., the range of thicknesses, the resolution, the material of the coating and the substrate, etc. Recently, terahertz measurement techniques reveal a high potential especially for nondestructive and contactless determination of multilayer systems. This technique can be used for a variety of dielectric coating systems nearly independently on the used substrate. Therefore, thickness measurements of coated paper and tablets as well as painted car bodies are typical applications.

While for the above mentioned applications the thickness is measured at the end of the complete coating process, i.e., after the final drying step, we here investigate the suitability of this technique for measurements right after application of the wet paint. This allows for certain corrections during painting to optimize the process itself. For this purpose we developed a special calibration method we call "self-calibration". Within the self-calibration process we simultaneously calculate the spectral material parameters as well as the thickness of the layer. In cooperation with industrial partners we checked several different coating systems on their consistency while observing the drying-process over time. A subsequent crosscheck after final drying with classical magneto-inductive measurements shows a very high correlation. Using terahertz measurement techniques in combination with our self-calibration method we are able to resolve the wedge-structure of the used samples in thickness from 100 μm down to 1 μm.

10103-26, Session 6

Film thickness determination using ultrashort terahertz pulses *(Invited Paper)*

Kodo Kawase, Kotaro Okimura, Nagoya Univ. (Japan); Yuji Nishizawa, JFE Steel Corp. (Japan); Kei Takeya, Nagoya Univ. (Japan)

INVITED PAPER: Non-contact layer thickness measurement method is important in various industrial applications. Conventional methods such as eddy current or electromagnetic inspection cannot always be used because the transducers must be in contact with the surface. The regular Terahertz-TDS (Time-domain Spectroscopy) system using a PCA (photoconductive antenna) is also inapplicable when the duration of the generated pulse is longer than the travel time within a thin film of approximately 10 um thick. In this research, a newly-developed THz-TDS system, which generates ultrashort pulses, was adopted for thickness measurement using a time of flight reflection tomography technique. The system is based on a Cherenkov phase matching mechanism using a MgO: $LiNbO_3$ ridge waveguide and generates a shorter and stronger pulse than the conventional TDS system which utilize a PCA. The measured sample is a thin plastic film (thinner than 20um) on metal substrate. THz pulses are irradiated to the sample, and time domain waveform is acquired by using a PCA as a detector. To resolve the reflected echoes from the film surface and the interface with the metal substrate, a deconvolution technique was applied to the acquired waveform. The thickness can be estimated by using a refractive index and the delay time. Estimation accuracy was sufficient, as estimation error was within 2um. This method is suitable for inline thickness measurement of thin films on production lines.

10103-27, Session 6

Online terahertz thickness measurement in films and coatings *(Invited Paper)*

Irl N. Duling III, Picometrix, LLC (United States)

Pulsed terahertz systems are currently being deployed for online process control and quality control of multi-layered products for use in the building products and aerospace industries.

While many laboratory applications of terahertz can allow waveforms to be acquired at rates of 1 – 40 Hz, online applications require measurement rates of in excess of 100Hz. The existing technologies of thickness measurement (nuclear, x-ray, or laser gauges) have rates between 100 and 1000 Hz. At these rates, the single waveform bandwidth must still remain at 2THz or above to allow thinner layers to be measured.

In the applications where terahertz can provide unique capability (e.g. multi-layer thickness, delamination, density) long-term stability must be guaranteed within the tolerance required by the measurement. This can mean multi-day stability of less than a micron.

The software that runs on these systems must be flexible enough to allow multiple product configurations, while maintaining the simplicity required by plant operators.

The final requirement is to have systems that can withstand the environmental conditions of the measurement. This might mean qualification in explosive environments, or operation in hot, wet or dusty environments. All of these requirements can put restrictions on not only the voltage of electronic circuitry used, but also the wavelength and optical power used for the transmitter and receiver.

The application of terahertz systems to online process control presents unique challenges that not only effect the physical design of the system, but can also effect the choices made on the terahertz technology itself.

10103-28, Session 6

Terahertz thickness measurements for real industrial applications: from automotive paints to aerospace industry

Soufiene Krimi, René Beigang, Technische Univ. Kaiserslautern (Germany)

In this contribution, we present a highly accurate approach for real-time thickness measurements of multilayered coatings using terahertz time domain spectroscopy in reflection geometry. The proposed approach combines the benefits of a model-based material parameters extraction method to calibrate the specimen under test, a generalized modeling method to simulate the terahertz radiation behavior within arbitrary thin films, and the robustness of a powerful evolutionary optimization algorithm to increase the sensitivity and the precision of the minimum thickness measurement limit. Furthermore, a novel self-calibration model is introduced, which takes into consideration the real industrial challenges such as the effect of wet-on-wet spray in the car painting process and the influence of the spraying conditions and the sintering process on ceramic thermal barrier coatings (TBCs) in aircraft industry. In addition, the developed approach enables for some applications the simultaneous determination of the complex refractive index and the coating thickness. Hence, a pre-calibration of the specimen under test is not required for such cases. Due to the high robustness of the self-calibration method and the genetic optimization algorithms, the approach has been successfully applied to resolve individual layer thicknesses within multi-layered coated samples down to less than 10 μm. The regression method can be applied in time-domain, frequency-domain or in both the time and frequency-domain simultaneously. The data evaluation uses general-purpose computing on graphics processing units and thanks to the developed highly parallelized algorithm lasts less than 300 ms. Thus, industrial requirements for fast thickness measurements with an "every-second-cycle" can be fulfilled.

10103-29, Session 6

An accurate frequency-modulated continuous-wave method for fast terahertz thickness measurements

Nina S. Schreiner, Bessem Baccouche, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Wolfgang Sauer-Greff, Ralph Urbansky, Technische Univ. Kaiserslautern (Germany); Fabian Friederich, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

While ultrasound and X-ray techniques are widely used for multilayer thickness measurements of dielectric materials in industrial environments, terahertz techniques complement these non-destructive testing methods and allow for contactless multilayer inspections without the need for radiation protection. Due to these combined advantages broadband terahertz systems are on the way to be established in the quality control for paint processes in the automotive industry. Nevertheless, in regard of thick plastic layers such as plastic tube walls with more than several millimeters of thickness, broadband terahertz signals suffer low penetration depths. In order to inspect plastic layers from millimeter to several tens of centimeters thickness at measurement rates of up to several kilohertz, we use electronic frequency modulated continuous wave terahertz systems operating in the terahertz regime below 500 GHz. The linear frequency modulated terahertz signal is sent by a transceiver unit to the sample-under-test such as a tube wall. Portions of the signal are reflected back from each boundary surface of the penetrated materials and are mixed with the currently transmitted signal of the transceiver. This will result in intermediate frequency signals whose frequencies are proportional to the depth of the respective boundary surface. Thereby the resolution is limited by the modulation bandwidth of the FMCW system and adversely affected by nonlinearities of the frequency sweep. Besides the necessary compensation of nonlinearities regarding the frequency sweep, we use signal processing techniques to enhance measurement accuracies down to a few tens of micrometers at sub-millimeter resolution.

10103-30, Session 7

Nyquist pulse generator by techniques of optical frequency shifting

Cheng Guo, Tianxin Yang, Zhaoying Wang, Dongfang Jia, Chunfeng Ge, Tianjin Univ. (China)

The demand of data transmissions among cloud database centers has grown up exponentially recent years, there has been a requirement for higher spectral efficiency.The Nyquist pulse source is an effectively solution to this issue, which can reduce security bandwidth for increasing the spectral efficiency. The concept of Nyquist pulses originates from data communication in electrical domain for saving microwave spectral resource. In optical domain, this kind of source has been newly developed based on active mode-locking technique in which a wavelength selective switch (WSS) has to be introduced in the cavity for modifying the profile of internal-cavity spectrum. The WSS is an advanced free-spaced optic-electrical array device which is hard to fabricate and expensive. In our work the Nyquist pulse train at repetition rate of 10GHz can be produced by external-cavity modulation technique along with intensity pre-distortion method without the need of expensive and free-spaced WSS devices. We use programmed electrical signal to drive an intensity modulator for pre-distortion the intensity of narrow linewidth continuous wave (CW) laser. Then the pre-distortion light is frequency shifted by the following optical fiber ring which consists of a single-sideband (SSB) modulator, an optical amplifier and optical bandpass filter. The simulation has been done, and the results of simulation is matched well with the experiments.

10103-31, Session 7

Microwave photonic filter with continuous tunability using a wavelength-spacing-tunable multiwavelength fiber laser

Young Bo Shim, Seung Min Lee, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

Microwave photonic filters have great potential in the application to Radio-over-Fiber (RoF) systems because they can provide by using microwave photonic filters the limitation of the traditional filters, e.g., the electric bottleneck problem and other sources of degradation. The wavelength spacing of the multiwavelength laser or the dispersion of the dispersive medium should be adjusted in order to control the free spectral range (FSR) of the microwave photonic filter. For the realization of multiwavelength laser with tunable wavelength spacing, tunable laser array was exploited. The FSR of the microwave photonic filter was tuned discretely by switching on and off the laser source. To realize multiwavelength in the single laser with the tunability of the wavelength spacing, tunable high birefringent Sagnac loop was used as a comb filter. However, since this scheme has only two wavelength spacings, the FSR of the microwave photonic filter could not be tuned continuously. In this manuscript, we demonstrate a novel continuously tunable microwave photonic filter based on a polarization differential delay line (PDDL). The continuously tunable multiwavelength laser was realized by using the Saganc loop mirror with the PDDL. By controlling the PDDL, the wavelength spacing of the multiwavelength laser was continuously controlled while the stable lasing output was maintained. As the wavelength spacing was adjusted from 1.2 to 6.8 nm with the extinction ratio of ~ 40 nm, the FSR of the microwave photonic filter was continuously controlled from 1.84 to 0.33 GHz.

10103-32, Session 7

Analogue RF-over-fibre links for future radar systems

Tamrha Thow, Leonardo-Finmeccanica (United Kingdom) and Univ. of Glasgow (United Kingdom); Anthony E. Kelly, Univ. of Glasgow (United Kingdom); Neil Raphael, Leonardo-Finmeccanica (United Kingdom)

This work demonstrates the performance that can be achieved by an analogue RF over fibre link designed using commercially available components. The aim of this work is to assess the suitability of such links for use in future radar systems. Coherent radar systems require high levels of performance in order to detect very small radar signals from within background clutter. The hardware required to achieve this needs to be highly linear, with very low additive noise and minimal electromagnetic interference, even when subjected to vibration and thermal variations. This includes the RF interconnect between subsystems. Future systems will require the distribution of increasing numbers of RF signals within ever decreasing size and weight budgets. RF over fibre links may offer a solution.

In this work an externally modulated direct detection link has been designed using a 1550 nm DFB laser module, a low V_ϖ Mach Zehnder modulator and a high responsivity p-i-n photodetector. The components were selected with the aim of minimising link loss without amplification, and to achieve a high dynamic range for operation at RF frequencies up to 20 GHz. The link gain, third order intercept and noise figure have been modelled and measured experimentally with good correlation between the two sets of results. These results demonstrate that the performance is predictable and should satisfy the linearity requirements for many radar applications.

10103-33, Session 7

Demonstration of compressive sensing RF signals using speckle in a multimode fiber

George A. Sefler, Thomas J. Shaw, Andrew D. Stapleton, George C. Valley, The Aerospace Corp. (United States)

In this talk we report experimental demonstration of compressive sensing (CS) with a complete photonic system in which the measurement matrix (MM) is implemented using speckle in a multimode waveguide. In our system, mode-locked femtosecond laser pulses are stretched in time, modulated by the RF signal, and launched into a 105-micron diameter multimode fiber. The output of the multimode fiber is imaged onto a 32-fiber bundle terminating into 32 independent integrating photodiodes and analog-to-digital converters (ADCs). Measurements are made at the laser repetition rate of 35.7 MHz of sparse signals with frequencies up to 5 GHz. Signal recovery is performed using Orthogonal Matching Pursuit (OMP), and we calibrate the CS MM by making measurements for a dictionary of single-frequency RF sinusoids. This can be the most practical method for MM calibration and signal recovery for a wideband system wherein the speckle pattern varies rapidly with wavelength.

10103-34, Session 7

Multicore fiber beamforming network for broadband satellite communications

Airat R. Zainullin, Ufa State Aviation Technical Univ. (Russian Federation) and Univ. Politécnica de Valencia (Spain); Borja Vidal, Andrés Macho Ortiz, Roberto Llorente Sáez, Univ. Politècnica de València (Spain)

Multi-core fiber (MCF) has been one of the main innovations in fiber optics in the last decade. Reported work on MCF has been focused on increasing the transmission capacity of optical communication links by exploiting space-division multiplexing.

Additionally, MCF presents a strong potential in optical beamforming networks. The use of MCF can increase the compactness of the broadband antenna array controller. This is of utmost importance in platforms where size and weight are critical parameters such as communications satellites and airplanes.

Here, an optical beamforming architecture that exploits the space-division capacity of MCF to implement compact optical beamforming networks is proposed, being a new application field for MCF. The experimental demonstration of this system using a 4-core MCF that controls a four-element antenna array is reported. An analysis of the impact of MCF on the performance of antenna arrays is presented. The analysis indicates that the main limitation comes from the relatively high insertion loss in the MCF fan-in and fan-out devices, which leads to angle dependent losses which can be mitigated by using fixed optical attenuators or a photonic lantern to reduce MCF insertion loss. The crosstalk requirements are also experimentally evaluated for the proposed MCF-based architecture. The potential signal impairment in the beamforming network is analytically evaluated, being of special importance when MCF with a large number of cores is considered.

Finally, the optimization of the proposed MCF-based beamforming network is addressed targeting the scalability to large arrays.

10103-35, Session 7

Wireless chemical sensor system based on electromagnetically energy-harvesting metamaterials

Wonwoo Lee, Yonghee Jung, Hyunseung Jung, Hojin Lee, Soongsil Univ. (Korea, Republic of)

In the past decade, there have been many studies on metamaterial based chemical and biological sensors due to their exotic resonance properties in microwave ranges. However, in spite of their non-destructive and highly sensitive properties, they have suffered from the use of bulky and expensive external measurement systems like a network analyzer for measuring resonance properties in the microwave regime. In this study, to increase accessibility of the metamaterial-based sensors, we propose a novel wireless chemical sensor system based on energy harvesting metamaterials at the microwave frequencies. The proposed metamaterial chemical sensor consists of a single split ring resonator and rectifier circuit to harvest the energy at the specific frequency, so that the chemical composition of the specific solution can be distinguished by the proposed metamaterial sensor by using the resonance property between the source antenna and the metamaterial which induces the variation in the energy harvesting rate of our sensor system. In our experimental setup, we used a 2.4 GHz Wi-Fi system as a source antenna. To verify the chemical sensitivity of the proposed sensor intuitively, we adopted a light emitting diode as an indicator of which luminescence is proportional to the energy harvesting rate determined by the ratio of ethanol and water in their binary mixture.

With these results, it can be expected that our metamaterial-based wireless sensor can pave the way to the miniaturized wireless sensor systems and can be applied to not only for the chemical fluidic sensors but also for other dynamic environment sensing systems.

10103-36, Session 8

Applications of spatially varying conductivity in plasmonics and metamaterials *(Invited Paper)*

Ashish Chanana, Andrew Paulsen, Ajay Nahata, The Univ. of Utah (United States)

Conventional plasmonic materials are typically fabricated using a single homogenous metal and structured to obtain useful functionality. Alternatively, structures are occasionally made in which several homogenous materials are deposited using a layer-by-layer process, such as metal-dielectric-metal structures [1]. However additional control over the propagation properties of surface plasmon-polaritons should be possible if the metal conductivity could also be varied spatially. This is not straightforward using conventional microfabrication techniques.

We demonstrate the ability to vary the conductivity spatially using a conventional inkjet printer, yielding either step-wise changes or continuous changes in the conductivity. We accomplish this using a commercially available inkjet printer, where one inkjet cartridge is filled with conductive silver ink and a second cartridge is filled with resistive carbon ink. By varying the fractional amounts of the two inks in each printed dot, we can spatially vary the conductivity. The silver ink has a DC conductivity that is only a factor of six lower than the bulk silver, while the carbon ink acts as a lossy dielectric at terahertz frequencies. Both inks sinter immediately after being printed on a treated PET transparency.

We demonstrate the utility of this approach with both plasmonics and metamaterial applications, demonstrating the ability to control beam profiles, create new filter capabilities and hide images in THz metasurfaces.

10103-37, Session 8

Terahertz modulators based on metasurfaces and metalines *(Invited Paper)*

Yan Zhang, Capital Normal Univ. (China); Tahsin Akalin, Univ. des Sciences et Technologies de Lille (France)

Metasurfaces are becoming one growing field of research in the domain of controlling electromagnetic waves. In this talk, we will focus on their design and applications at terahertz frequencies. The state of the art for terahertz modulators will be particularly described and original terahertz modulators will be presented. With metasurfaces, we will particularly focus on the control of the amplitude with checkerboard topologies and also the phase and the polarization with SRR or V-shape meta-atoms. One part will be dedicated to flat lenses with the spin selection of the impinging waves. The second part will be dedicated to a review of recent results on the use of Plan! ar Goubau Lines combined with meta-atoms or with corrugations.

10103-38, Session 8

Large dynamic range terahertz spectrometers based on plasmonic photomixers *(Invited Paper)*

Ning Wang, Univ. of California, Los Angeles (United States); Hamid Javadi, Jet Propulsion Lab. (United States); Mona Jarrahi, Univ. of California, Los Angeles (United States)

Heterodyne terahertz spectrometers are highly in demand for space explorations and astrophysics studies. A conventional heterodyne terahertz spectrometer consists of a terahertz mixer that mixes a received terahertz signal with a local oscillator signal to generate an intermediate frequency signal in the radio frequency (RF) range, where it can be easily processed and detected by RF electronics. Schottky diode mixers, superconductor-insulator-superconductor (SIS) mixers and hot electron bolometer (HEB) mixers are the most commonly used mixers in conventional heterodyne terahertz spectrometers. While conventional heterodyne terahertz spectrometers offer high spectral resolution and high detection sensitivity levels at cryogenic temperatures, their dynamic range and bandwidth are limited by the low radiation power of existing terahertz local oscillators and narrow bandwidth of existing terahertz mixers. To address these limitations, we present a novel approach for heterodyne terahertz spectrometry based on plasmonic photomixing. The presented design replaces terahertz mixer and local oscillator of conventional heterodyne terahertz spectrometers with a plasmonic photomixer pumped by an optical local oscillator. The optical local oscillator consists of two wavelength-tunable continuous-wave optical sources with a terahertz frequency difference. As a result, the spectrometry bandwidth and dynamic range of the presented heterodyne spectrometer is not limited by radiation frequency and power restrictions of conventional terahertz sources. We demonstrate a proof-of-concept terahertz spectrometer with more than 90 dB dynamic range and 1 THz spectrometry bandwidth.

10103-39, Session 8

Analysis of tuning methods in semiconductor frequency-selective surfaces *(Invited Paper)*

Corey M. Shemelya, Dominic Palm, Tassilo Fip, Marco Rahm, Technische Univ. Kaiserslautern (Germany)

Advanced technology devices, such as sensing and communication equipment, have recently begun to combine optically sensitive nano-scale structures with customizable semiconductor material systems. Included within this broad field of study is the aptly named frequency-selective surface; which is unique in that it can be artificially designed to produce a specific electromagnetic or optical response. One of the relatively new and exciting advancements in the field is the development of dynamic, or tunable, frequency-selective surfaces. These devices are designed to alter the optical response of a surface through the application of external stimuli; therefore, this study focuses on the advancement of multiple metamaterial tuning mechanisms in the THz frequency region.

The field of dynamic frequency-selective surfaces, through optical or electrical tuning, has had exciting breakthroughs since the initial conception; however, these methods are typically energy intensive (optical tuning) or have met with limited success (electrical tuning). As such, this work investigates the fundamental processes observed when implementing semiconductor electrical biasing and/or optical tuning in these dynamic surfaces. Within this study are surfaces ranging from transmission meta-structures to metamaterial surface waves and couplers. This work shows the utility of each design, while highlighting potential methods for optimizing dynamic meta-surfaces. For experimental investigation, a state-of-the-art Ti:Sapphire Spitfire® Ace and Spitfire® Ace PA dual system (12 Watt) with pulse front matching THz generation and an EOS detection system are used. The Ti:Sapphire laser system also provides optical tunablity, while electrical tuning is obtained through external power supplies.

10103-40, Session 8

Broadband terahertz generation from metamaterials and their hybrid quantum structures *(Invited Paper)*

Jigang Wang, Iowa State Univ. of Science and Technology (United States)

The terahertz spectral regime, ranging from about 0.1–15 THz, is one of the least explored yet most technologically transformative spectral regions. One current challenge is to develop efficient and compact terahertz emitters/detectors with a broadband and gapless spectrum that can be tailored for various pump photon energies. A particularly essential and topical question is how to create nonlinear broadband terahertz devices using deeply subwavelength nanoscale meta-atom resonators.

Here we demonstrate efficient single-cycle broadband THz generation, ranging from about 0.1–4 THz, in two model hybrid quantum nanostructures: (1) a thin layer of split-ring resonators (SRRs) with few tens of nanometers thickness by pumping at the telecommunications wavelength of 200 THz; (2) SRRs coupled to intersubband transitions in quantum wells pumping at 30 THz. We also reveal a giant sheet nonlinear susceptibility that far exceeds thin films and bulk non-centrosymmetric materials. Finally, I will also discuss their significances for THz enabled nonlinear spectroscopy and quantum phase discovery applications.

10103-41, Session 9

Terahertz medical imaging: cancer diagnosis *(Invited Paper)*

Pallavi Doradla, Wellman Ctr. for Photomedicine (United States) and Univ. of Massachusetts Lowell (United States); Cecil S. Joseph, Robert H. Giles, Univ. of Massachusetts Lowell (United States)

Terahertz (THz) imaging is emerging as a robust platform for a myriad of applications in the fields of security, health, astronomy and material science. Due to the non-ionizing nature, the terahertz regime with wavelengths spanning from microns to millimeters is potentially a safe and noninvasive medical imaging modality for detecting cancers. Cancers figure among the leading causes of death worldwide with more than 14 million new cases diagnosed each year. The presence of cancer often results in increased blood supply and local increment in tissue water content. As a result of its sensitivity to water content, terahertz imaging provides natural contrast between cancer and normal regions. The structural changes of abnormal tissue often attribute to additional intrinsic terahertz imaging contrast. Recent studies have affirmed the use of terahertz frequencies in cancer detection and demonstrated an intrinsic contrast between normal and abnormal regions of skin, dental, breast, liver, gastric, and colorectal tissue. Pragmatically, the endoscopic imaging systems provide high flexibility in examining the interior surfaces of an organ and body cavities. Researchers have been working on the development of medical terahertz imaging systems to aid the conventional cancer screening methods. This involves building a single-channel flexible terahertz endoscopic system, and investigating the terahertz response from cancerous colon, and demonstrating observable contrast levels when imaging in reflection modality. The current level of contrast attained by prototype terahertz endoscopic systems represents a significant step towards clinical endoscopic application of terahertz technology for in-vivo cancer screening. The aim of this talk is to provide a review of the recent advances in terahertz endoscopic technology and cancer imaging.

10103-42, Session 9

One-dimensional photonic crystals for eliminating cross-talk in mid-IR photonics-based respiratory gas sensing

Lewis S. Fleming, Univ. of the West of Scotland (United Kingdom); Des Gibson, Univ. of the West of Scotland (United Kingdom) and Gas Sensing Solutions Ltd (United Kingdom); Shigeng Song, David Hutson, Stuart Reid, Univ. of the West of Scotland (United Kingdom); Calum MacGregor, Gas Sensing Solutions Ltd (United Kingdom);

Caspar Clark, CJS Instrumentation Ltd (United Kingdom)

Mid IR narrow band optical filters are designed, manufactured and analysed for the purpose of reducing the effective spectral response of a photonics based CO2 gas sensor. The sensors operate by using an LED-photodiode combination, grown by molecular beam epitaxy with a stoichiometry tuned for emission and detection at the CO2 absorption band wavelength. As the total detection bandwidth of the sensor spans 2500 nm to 5000 nm, the sensor is sensitive to any gas with absorption peaks in this region therefore optical filtering is necessary to provide wavelength discrimination and target detection gas specificity. Gases with appreciable absorption bands in this region include N2O, H2O, CH4 and CO. Of particular interest in the medical field of capnography - the monitoring of exhaled CO2 in the respiratory gases - are crosstalk due to H2O and N2O. The human breath contains near 100% RH. Also N2O is widely used in surgical anaesthesia where CO2 monitoring is largely employed. These gases have absorption bands at 2.8 um and 4.5 um for H2O and N2O respectively, lying within the 2500 nm to 5000 nm total spectral response of the gas sensor. This results in false CO2 readings when these gases are present. The energetic deposition technique of reactive DC magnetron sputtering is employed to manufacture dense, durable thin film optical filters to filter out wavelengths outwith the CO2 absorption band. Different multilayer stacks and their performance are modelled in silico and attempts are made to manufacture such designs in the lab. Filter performance is tested using an in house NDIR optical gas filter test bed.

10103-43, Session 9

Tissue characterization by using phase information of terahertz time domain spectroscopy

Hiroaki Fukuda, Ricoh Co., Ltd. (Japan); Tsubasa Minami, Kodo Kawase, Nagoya Univ. (Japan)

A non-invasive, unstaining tissue measurement method is expected to be an important tool for regenerative medical. As THz wave do not affect biological tissue because of their low energy, THz measurement method is expected to become a new modality of biomedical analysis as a noninvasive diagnosis. Due to the fact that biological tissues possess high level of hydration, it results in strong absorption at terahertz frequencies. A ridge waveguide LiNbO3 based nonlinear terahertz generator was used to achieve high output power for THz time domain spectroscopy (THz-TDS). A ridge waveguide was designed for high efficiency emission from the LiNbO3 crystal by the electro-optic Cherenkov effect. This THz-TDS system has realized six orders of dynamic range, and the bandwidth of the spectrum reaches 7 THz in the upper limit. We measured a reflected terahertz pulse shape at the interface between a plastic culture dish and biological tissues. By studying the gradient of phase spectroscopy of reflected THz pulse, we have been able to differentiate between human fibroblast tissue and cancer tissue. We demonstrate the application of terahertz time domain spectroscopy pulse in reflection geometry for the non-distractive measurement of biological tissues cultured on a plastic culture dish. These results demonstrate the potential of terahertz phase information for the study of biological tissues.

10103-50, Session 10

Terahertz chiral structures with large optical activity

Michael A. Cole, The Australian National Univ. (Australia); Wen-chen Chen, Boston College (United States); Willie J. Padilla, Duke Univ. (United States); Sergey S. Kruk, David A. Powell, Ilya V. Shadrivov, The Australian National Univ. (Australia)

Metamaterials are subwavelength man-made plasmonic or dielectric structures designed to realize specific effects on the electromagnetic radiation interacting with the material. Here we aim to rotate the polarization of an incident terahertz beam using chiral metamaterials, while suppressing the circular dichroism which induces ellipticity of the output beam. An incident linearly polarized wave can be decomposed into left-circularly and right-circularly polarized waves, and the difference in propagation phase will result in rotation of the plane of polarization. Since chiral structures couple electric and magnetic fields, they are often implemented in complex geometries such as spirals or bi-layered plasmonic structures, which can achieve carefully balanced responses to the two fields. The important feature of the bi-layered plasmonic structure is the cross-coupling between the resonances of the two layers. It is precisely this coupling between the layers that induces currents in the structures that are mutually dependent producing chirality within the structure. By coupling a metallic structure to its complement, we are able to achieve strong transmission in the region of maximum polarization rotation, and relatively low ellipticity of the output state. Three different structures were fabricated for this work that will be referred to as: the plain crosses, crossed arrowheads, and crossed arcs, pictured in the figure below. The terahertz responses of the structures were compared using terahertz time-domain spectroscopy and numerical simulations using CST Microwave Studio software.

10103-51, Session 10

Improvement of terahertz time-domain spectroscopy precision by interferometrically-tracked delay lines

Daniel Molter, Manuel Trierweiler, Frank Ellrich, Joachim Jonuscheit, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Georg von Freymann, Technische Univ. Kaiserslautern (Germany) and Fraunhofer-Institut für Physikalische Messtechnik (Germany)

Applications of terahertz time-domain spectroscopy rely on the accuracy of the assignment of amplitudes to the corresponding time stamp – no matter if the application bases on the analysis of data in the time or frequency domain. As these two domains are directly related via Fourier-transformation, inaccuracies and errors in the time domain directly imply errors in the frequency domain. Therefore, the knowledge of the correct time delay – which is in the case of time-domain spectroscopy systems the knowledge of an optical path length – is of utmost importance for exact results. Common time-domain spectroscopy systems measure mechanical translations (or rotations) and calculate the optical path length based on these measurements. However, the problem is that the optical components are often moving on an axis far away from the axis of the measurement component. In linear translation stages mechanical deviations as pitch and yaw produce errors that make the assumption of the optical beam path length imprecise and wrong. In our approach, we exactly measure the optical path length by overlapping the femtosecond pulses used to drive emitter or detector of the time-domain spectroscopy system with a continuous-wave laser beam from one branch of a displacement measurement interferometer. Our results show excellent agreement of the acquired spectra to simulated spectra of water vapor absorption lines using the HITRAN database, even when driving the optical delay line with imprecise components as RC model servo motors.

10103-52, Session 10

Functional flexible metasurface

Yair D. Zarate, Ilya V. Shadrivov, David A. Powell, The Australian National Univ. (Australia)

Metasurfaces represent the most promising class of metamaterials for real applications, whereby arbitrary wavefront and polarisation control can be achieved using just a single sub-wavelength layer. Therefore, allowing

tunability over their capabilities is the next step to consolidate them as technology devices for light control. In our work we propose a new platform for creating tunable microwave devices based on gradient metasurfaces. Our study shows that the integration of a patterned elastic substrate in the design of functional metasurfaces is an effective approach to enable control over their electromagnetic properties.

To demonstrate the new platform, we propose, design and experimentally realize a novel tuning mechanism that controls the focal length of an electromagnetic metasurface lens by exploiting the degree of freedom provided by the flexible substrate, which enables continuous elongation of the system. When such a metasurface is uniaxially stretched, the distance between embedded electromagnetic resonators increases, producing a change in the phase profile created by these resonators, and this leads to a change of the focal distance of the lens. Thus, the flexible metasurface displays a functionality that can be continuously controlled by unidirectional mechanical loading. We fully characterize the spherical-like aberration phenomenon which accompanies the tuning process. Finally, our study reveals that an equidistant separation between the resonators leads to reduced device performance of the operational metasurface and, therefore, the utilization of other degrees of freedom is mandatory if the efficiency needs to be preserved.

10103-53, Session 10

Demultiplexing method of terahertz-wave OFDM sub-carrier channels using integrated-optic DFT circuit

Koichi Takiguchi, Ritsumeikan Univ. (Japan)

Terahertz-wave communication is attractive because it can provide high-speed wireless communication more than 10 Gbit/s, which is suitable for transmitting high-resolution images. Although the single-carrier transmission is being vigorously pursued to develop high-speed terahertz-wave communication, it is also important to develop?multi-carrier terahertz-wave communication including orthogonal frequency division multiplexing (OFDM) when considering the future bursty increase in traffic. However, it is difficult to demultiplex a high-speed OFDM signal more than several tens of gigahertz in real time with an electronic circuit. In this presentation, I propose and report a real-time demultiplexing method for the terahertz-wave OFDM signal, which utilizes the optical technology. The terahertz-wave OFDM signal is generated by mixing an optical OFDM signal with a continuous-wave lightwave in a uni-traveling carrier photodiode. In the terahertz-wave receiver, a baseband electrical OFDM signal is produced at the mixer. The linearly amplified baseband OFDM signal is transferred into an optical OFDM signal through an optical modulator. Then, the produced optical OFDM signal is processed with an integrated-optic discrete Fourier transform (DFT) circuit fabricated with silica waveguide technology, which is composed of a splitter, an array of delay lines, and a slab star coupler. This optical DFT circuit is compact (20 mm x 45 mm), and can process up to a 10 sub-carrier x 10 Gbaud (100 Gbaud) OFDM signal. I report the configuration and operating principle of the method, its characteristics estimation, and preliminary experimental results to show its effectiveness. A several tens of gigahertz terahertz-wave OFDM signal was successfully demultiplexed with the method, which was assisted by the optical technology. This work was supported by the MIC/SCOPE #165007001.

10103-45, Session 11

Metamaterial reconfigurable spatio-temporal modulators for terahertz sensing and imaging *(Invited Paper)*

Willie J. Padilla, Duke Univ. (United States)

Metamaterials consisting of a single functional layer – termed metasurfaces – have demonstrated the capability to perform advanced modulation at terahertz frequencies. Metasurface modulators may be formed into spatial light modulators (SLMs) and the all electronic solid-state control permits advanced modulation states difficult to implement with other SLMs. We present results of active metamaterial spatial light modulators used for single pixel imaging at THz frequencies. We further parallelize the imaging process by implementing quadrature amplitude modulation and frequency diversity.

Our metamaterial pixel consists of absorbers with a maximum absorption of 85% at 3.1 THz. The metamaterial absorber consists of two metallic layers with a semiconductor (GaAs) lying in-between. The GaAs is doped to a carrier density of 1e16/cm3 and we apply a bias to deplete charges, thus effectively modulating the absorption peak frequency. The left panel of Figure 1 shows a 8 ? 8 metasurface SLM fabricated for operation at THz frequencies. The right panel shows a simulation of an active semiconductor-based metamaterial which is used to provide a holographic image in the far-field.

Metamaterial-based spatial light modulators are useful for a host of applications including imaging and holography. We overview the use of metamaterial digital spatial light modulators for single pixel imaging in the terahertz regime. The theory of coded aperture imaging is discussed and the future potential applications of this exciting field are discussed.

10103-46, Session 11

Ultrathin wide bandwidth metamaterial absorber using randomly distributed scatterers

Farzad Ahmadi, Nathan Ida, The Univ. of Akron (United States)

The advent of metamaterials has opened up new frontiers for researchers because of their extraordinarily properties in a wide range of applications including cloaking, optical filters, holography and super lenses. Metamaterials are well designed arrays of periodically distributed scatters on conventional materials. Since manipulating electromagnetic (EM) waves is their exceptional property, absorbing EM waves using metamaterials revolutionized traditional absorbers to design ultrathin and broadband absorbers. Most current Metamaterial Absorbers (MAs) are developed and are studied based on array of periodic unit cells.

However, in this paper, a broadband, ultrathin MA using randomly distributed scatterers is presented. Each scattering element consists of two parallel tilted strips. These elements can either be isolated or have overlap with nearby elements. Three different randomly distributed structures are investigated for normal incident angle as well as oblique incident angles showing that these MAs can provide broadband absorption for all cases. The results presented here coincide with some previous works. Each structure obviously performs different absorption spectrum and FWHM since the coupling between the randomly positioned scatterers are different in each case. The coupling between neighboring isolated and clustered scatterers form many resonating modes resulting in broadband absorption. The distribution of the electromagnetic fields are analyzed to obtain the physical behavior of the absorber. This shows that promising results can still be obtained for MAs when there is a significant tolerance distance between scatters due to the fabrication process errors in micro and nanoscale metadevices.

10103-48, Session 11

High-performance terahertz metasurface lenses *(Invited Paper)*

Hou-Tong Chen, Los Alamos National Lab. (United States)

Tailoring the geometry and arrangement of metasurface structures yields a complete control of the reflection/transmission amplitude, phase, and polarization states. The planar nature of the structures can be readily fabricated using existing technologies, which makes them more accessible

particularly in the optical regime and potentially revolutionizes the design of integrated photonics. Although the ultrathin thickness in the wave propagation direction can greatly suppress the absorption, the impedance mismatching in many metasurfaces results in undesirable high insertion losses, and the performance of single-layer metasurface devices is yet unsatisfying in real world applications. In contrast, few-layer meta-surfaces can circumvent this impedance mismatching issue. Recently, we have developed a three-layer metasurface structure that is capable of rotating the incident linear polarization by 90° with a very high efficiency over a bandwidth of nearly two octaves. More importantly, the phase of the output light can be tuned over the entire 2ϖ range with sub-wavelength resolution through simply tailoring the structure geometry of the basic building blocks. This creates an important opportunity in designing highly efficient optical devices for wavefront engineering, such as at lenses working in the microwave, terahertz, and infrared frequency ranges. Here we will present the design, fabrication, and characterization of high-performance terahertz metasurface lenses based on this concept.

10103-49, Session 11

Tunable THz metamaterials based on phase-changed materials (VO2) triggered by thermal and electrical stimuli

Aurelian Crunteanu-Stanescu, Georges J. Humbert, Jonathan Leroy, Laure Huitema, Jean-Christophe Orlianges, Annie Bessaudou, XLIM Institut de Recherche, Univ. de Limoges (France)

Despite a high application potential, the using of THz frequencies is currently limited by the small number of existing terahertz components and, particularly, of tunable THz devices. Here we demonstrate the possibility of realizing tunable THz devices by introducing a phase change material (vanadium dioxide -VO2) as localized patterns in the structure of THz planar metamaterials.

VO2 is undergoing a reversible insulator-to-metal transition (MIT) when heated above ~341K. The transition is accompanied by abrupt changes in the material's electrical and optical properties (electrical resistivity decreases by 5 orders of magnitude while the optical properties are significantly modified). The MIT in VO2 can be triggered not only thermally but also electrically or optically. Activation times as short as 100 fs has been reported for the optically-driven MIT, while the electronic transition occurs on nanoseconds timescales. These characteristics allow extensive design flexibility for material integration in high-frequency applications.

One of the most peculiar characteristics of the VO2 material is its broadband MIT response, manifested by drastic electrical and dielectric properties changes between the insulator and metallic states on a very large frequency spectrum.

We are presenting the characterization of the MIT in VO2 films over a wide range of the electromagnetic spectrum (100MHz-67GHz, 75-110GHz, 0.1-1.4THz) and illustrate the materials' capabilities in the millimeter-waves and THz domains. We designed, simulate and fabricated tunable VO2-based THz metamaterials devices which show significant variations in their THz transmission under the effect of thermal stimuli but also by applying an electrical voltage across the devices.

10103-75, Session 11

Detecting and identifying DNA via the THz backbone frequency using a metamaterial-based label-free biosensor

Sahar Mirzaei, Nicolas Gavin Green, Mihai Rotaru, Suan Hui Pu, Univ. of Southampton (United Kingdom)

In genetic diagnostics, analysis is typically based on fluorescent labelling of target DNA, which is time-consuming, expensive and can fundamentally alter the target. For benchtop diagnostics, the technological requirement for optically reading the labels makes devices more complex. This paper presents a metamaterial-based THz sensor intended to resolve these issues and provide a high sensitivity label-free measurement of the natural backbone resonance of DNA in the THz range.

The proposed metamaterial structure uses asymmetric resonant structures as inclusions in a composite surface material to generate a trapped-mode resonance with a high quality factor. The resonators are X-shaped, tuned to produce trapped-mode resonances in the THz regime, with the asymmetric arms having two different resonant frequencies close to one another. The resulting trapped-mode has a high Quality-factor, which is ideal for sensing.

The structures and responses were simulated using a combination of different simulation packages and the optimum design of the gold resonators, substrate material and support were determined. DNA samples were modelled as layers on top of the resonating structure and the sensitivity of the structure calculated by examining the change in the resonant frequency. The trapped-mode requires a difference between pairs of arms but the degree of difference does not have a large impact on the sensitivity. The best Quality-factor (≈118) was found for a separation of 80 degrees between matching arms. The best substrate material was identified as quartz, which has reasonable transparency in THz and the effect of etching the substrate beneath the resonator was also modelled.

10103-68, Session PWed

Precisely tunable multi-wavelength fiber laser source for phased array antenna

Tao Du, Zhaoying Wang, Quan Yuan, Rui Ma, Qiyu Wang, Tianxin Yang, Tianjin Univ. (China)

Multi-wavelength fiber optical sources with tunable wavelength spacing have attracted much attention due to their potential applications in the fields of phased array antenna, laser radar imaging and real-time spectral analysis. However the existing tunable multi-wavelength fiber optical sources suffer a major disadvantage that the tunable wavelength spacing of multi-wavelength fiber optical sources is not precise attributed to employing mechanical tunable devices.

In this letter, a multi-wavelength fiber optical source with precisely tunable wavelength spacing is proposed and demonstrated by employing a distributed feedback laser (DFB), a single-side-band (SSB) modulator and a highly nonlinear fiber (HNLF).The DFB is used to launch the seed laser into the SSB. The SSB is employed to modulate seed laser to generate side frequency laser. By employing the HNLF to induce four-wave mixing effect and cascade four-wave mixing effect, more side frequency laser is stimulated. Then multi-wavelength is formed. The frequency spacing of the multi-wavelength equals to the radio frequency signal that drives the SSB modulator. Accordingly the wavelength spacing of the fiber laser source can be precisely tuned by adjusting the frequency of the radio frequency signal. In our experiments, up to 41stable lasing lines with 0.08 nm (10GHz) spacing and 29lasing wavelengths with 0.12 (15GHz) nm spacing within 3 dB bandwidth were obtained at room temperature. By adjusting the output frequency of the radio frequency signal generator, the wavelength spacing of the sources can be tuned to 20GHz and the precise of the sources reaches Hz level.

10103-69, Session PWed

A linearly frequency-swept high-speed-rate multi-wavelength laser for optical coherence tomography

Qiyu Wang, Zhaoying Wang, Quan Yuan, Rui Ma, Tao Du, Tianxin Yang, Tianjin Univ. (China)

We proposed and demonstrated a linearly wavenumber-swept multi-wavelength laser source for optical coherence tomography (OCT) without wavenumber space resampling. The source consists of a multi-wavelength fiber laser source (MFS) and an optical sweeping loop. The MFS outputs equally spaced multi-wavelength laser to be circularly step-like swept in the optical sweeping loop. Within each period of the square signal applied to the RF generator, the multi-wavelengths from MFS are swept with a certain step in the wavenumber domain. The sweeping step controlled by the RF signal applied to the optical sweeping loop is constant as the phase noise of the RF signal is lower than -104dBc/Hz. So the sweeping is time-wavenumber linear. The linear wavenumber-sweeping ensures linearly sampling in wavenumber domain for OCT, thus reducing the need for recalibration and resampling before fast Fourier transforming. In addition, for a certain sweeping range, the sweeping speed for OCT by using our laser source can be multiplied as compared with single wavelength sweeping. Furthermore, this electronic control sweeping technique eliminates the mechanical limitations in wavelength sweeping. By precisely electrical controlling, this linearly swept source can provide a complete spectrum for OCT imaging. Experimentally, we achieve a sweeping rate of 400 kHz at a sweeping step of 10GHz.

10103-70, Session PWed

Ultra-flattened nearly zero-dispersion THz waveguide using photonic quasi-crystal porous core fiber

Soeun Kim, Yong Soo Lee, Gwangju Institute of Science and Technology (Korea, Republic of); Chung Ghiu Lee, Inkyu Moon, Chosun Univ. (Korea, Republic of)

Terahertz (THz) waves are finding growing applications in various important fields such as astronomy, imaging, security screening, pharmaceutical quality control and communications. To date, most of THz systems are bulky and rely on free space propagation due to the lack of effective transmission devices in the THz region. Photonic crystal fibers (PCFs), consisting of a central defect region surrounded by air holes running parallel to the fiber length, have attracted considerable attention due to their unique properties, such as high birefringence, endless single mode guidance, wide band ultra-flattened dispersion, dispersion compensation, high nonlinearity. Recently, there have been reports of using plastic PCFs as THz waveguides Nevertheless, absorption loss in the solid core PCFs are too high almost equal to the bulk absorption loss of the material. More recently, different research groups demonstrated several concepts to improve field confinement in the core region of PCF by introducing pores in the core surrounded by the air cladding. This concept is also used to reduce the material loss for transmission of THz waves within the core. In this paper, we present the photonic quasicrystal porous core THz fiber with high birefringence and low dispersion. Photonic quasicrystal fiber is a special device which has been able to overcome the limitations of the PCFs. In this work, we design a PQF of 6, 8, 10-folds to study the guiding properties in THz region and optimize the structure to meet the requirement of high birefringence with the order of 10-2 and low dispersion.

10103-71, Session PWed

Slot-shaped porous core THz photonic crystal fiber with broadband high birefringence and nearly zero flat-dispersion

Soeun Kim, Yong Soo Lee, Gwangju Institute of Science and Technology (Korea, Republic of); Chung Ghiu Lee, Chosun Univ. (Korea, Republic of)

In recent years, much effort has been devoted to Terahertz (THz) waves for its great potential in many applications such as astronomy, imaging, security screening, pharmaceutical quality control and communications. Most of THz systems are bulky and rely on free space propagation due to the lack of effective transmission devices in the THz region. More recently, different research groups demonstrated several concepts to improve field confinement in the core region of PCF by introducing pores in the core surrounded by the air cladding. This concept is also used to reduce the material loss for transmission of THz waves within the core. Several porous core PCFs have been reported claiming to be suitable for THz transmission. In this paper, we propose another type of poeoua core design. Slot shaped air holes are embedded in the rectangular core region surrounded by square lattice arranged cladding in order to control polarization and dispersion property maintaining low absorption loss. To the best of our knowledge, this type of slot-shaped porous core PCFwith broadband uniform and high birefringence and nearly zero flat dispersion has never been discussed in THz fiber research.

10103-72, Session PWed

Self-oscillating optical comb generator based on optoelectronic oscillator

G. Kibria M. Hasanuzzaman, Stavros Iezekiel, Univ. of Cyprus (Cyprus)

This work is focused on two promising concepts of microwave photonics-optoelectronic oscillators and optical frequency comb generators, and their use to generate a self-oscillating optical comb. In particular we develop a recirculating loop topology in which a Mach-Zehnder modulator is modulated recursively via a secondary loop that acts as a self-homodyne input.

First, a directional coupler is used to split the optical power radiated form a continuous wave laser. One output of the coupler is fed to the modulator after converting to the electrical domain via a fast photodetector. The other output of the coupler is connected as an input to a Mach-Zehnder modulator. The MZM is biased at the quadrature point and creates side bands equal to the frequency of the oscillation. The output of the modulator is passed through a single mode fiber which acts as the resonator section of the OEO and an optical band pass filter prior to connection to one input of the coupler. Since the double sideband MZM is connected via feedback it provides a stable comb output. Simulation results (spectral response and phase noise characteristics) using VPI transmission maker are discussed. The self-oscillating comb can be utilized to generated high quality millimeter wave and terahertz signals without any reference signal, which can have further applications for radio over fiber links with high date rates.

10103-73, Session PWed

An inset-fed slot ring antenna integrated with a terahertz photomixer based on a uni-traveling-carrier photodiode

Han-Cheol Ryu, Sahmyook Univ. (Korea, Republic of); Eui Su Lee, Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of); Min Yong Jeon, Chungnam National Univ. (Korea, Republic of)

We propose an inset-fed slot ring antenna to optimally match with a uni-traveling-carrier photodiode (UTC-PD) type terahertz (THz) photomixer. The impedance of a UTC-PD is high compared to the impedance of a usual broadband antenna. A control of the impedance of the resonant antenna and a proper impedance matching between the antenna and the photomixer are very important to increase the THz output power. Several factors have been studied to control the impedance matching condition in the device composed of an antenna and a UTC-PD photomixer with a bias circuit, such as size of slot ring, geometry of the inset, a photomixer position, and so on. Especially, the notch gap and feed line geometry of the inset-fed slot ring antenna has been investigated for the control of the antenna impedance.

And, the length of the coplanar waveguide (CPW) connecting the antenna with the photomixer was intensively studied to enhance the impedance matching properties. The bias circuit integrated in the device for the operation of the UTC-PD was also optimized for the impedance matching of the device. The optimization method of the inset-fed slot ring antenna can successfully control the antenna impedance to match with a UTC-PD type terahertz photomixer. The proposed inset-fed slot ring antenna can optimally match with a terahertz photomixer having various impedance and effectively increase the output power of the device based on the photomixer in the terahertz frequency region.

10103-74, Session PWed

Analysis of quantum well optical modulation in light-emitting transistors

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With enhanced carrier recombination rate and embedded quantum wells (QWs) in base region of hetero-junction bipolar transistors, lighting emitting transistors (LETs) were invented by Feng and Holonyak in 2004. The new transistor generates electronic and photonic outputs simultaneously, resulting in a considerable candidate in the application of optoelectronic integrated circuits. The modulation bandwidth of spontaneous optical emission in LETs up to 4.3?GHz has been achieved, which makes LETs potential light emitters in the optical communication systems.

Thus, a study of the optical modulation mechanism should serve as a key to increase the device bandwidth.

The overall optical modulation are separated into E-to-E modulation transfer function and E-to-O transfer functions, which are modeled with measured scattering parameters in common-emitter, common-base and common-collector configurations.

Former study on this topic has been demonstrated with T-model configuration of HBTs, which emphasizes in the circuit configuration analysis, and lacks the link to charge recombination mechanism. In this work, we perform a charge modulation analysis and the link to a Pi small-signal circuit model.

In this Pi model approach, we could directly link minority charges to optical modulation with corresponding admittance, while T model approach only see depletion charges and lacks the mechanism of charge recombination.

Furthermore, a different recombination branch on the small signal circuit model is also presented. With the new proposed recombination branch and matched simulated model to measured data, the link to device physical model is discussed and a better circuit model is proposed.

10103-54, Session 12

Resonant tunnelling diode terahertz sources for broadband wireless communications *(Invited Paper)*

Edward Wasige, Khalid Alharbi, Abdullah Al-Khalidi, Jue Wang, Univ. of Glasgow (United Kingdom); José Figueiredo, Univ. do Algarve (Portugal)

This paper will discuss resonant tunnelling diode (RTD) sources being developed on a European project iBROW (ibrow.project.eu) to enable short-range multi-gigabit wireless links and microwave-photonic interfaces for seamless links to the optical fibre backbone network. The practically relevant output powers are at least 10 mW at 90 GHz, 5 mW at 160 GHz and 1 mW at 300 GHz and simulation and some experimental results show that these are feasible in RTD technology. To date, 75 - 315 GHz indium phosphide (InP) based RTD oscillators with relatively high output powers in the 0.5 – 1.1 mW range have been demonstrated on the project. They are realised in various circuit topologies including those that use a single RTD device, 2 RTD devices and up to 4 RTD devices for increasingly higher output power; indeed, an oscillator employing 4 RTD devices provided a record 1.1 mW at 315 GHz. Besides device sizing and multi-device oscillators, epitaxial device designs for high power will also be discussed. The oscillators are realised using only photolithography by taking advantage of the large micron-sized but broadband RTD devices. The paper will also describe the integration of RTD devices with laser diodes or as photo-detectors which makes this a unified technology that can be integrated into both ends of a wireless link, namely consumer portable devices and fibre-optic supported base-stations.

10103-56, Session 12

Properties of cellulose nanocrystal films and powder in the terahertz frequency regime

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The terahertz (THz) radiation properties of cellulose nanocrystal (CNC) films, a CNC powder, and a dissolving pulp (ie: cellulose) film are investigated using THz time-domain spectroscopy. CNCs are the fundamental structure of each film; however, the source from which these nanocrystals are extracted and the techniques used to dry these nanocrystals into films vary. Transmission experiments are performed to determine the optical properties of the CNC films and powder, as well as the dissolving pulp film, at frequencies between 0.2 and 1.5 THz. For the CNC samples, the real component of the relative permittivity is found to vary between 1.78 and 3.81, despite the fact that they are made from the same linear chain of glucose monomers. As such, the permittivity is strongly dependent on the source from which the CNC glucose monomers are extracted, as well as the technique used to dry the films. CNC is attractive for use in both passive THz device and potential THz bandwidth electronic components. This is due to the materials growth-varying permittivity, THz loss tangent (0.043 < tan(?) < 0.145), absorption coefficient (3.5 cm-1 < ? < 63.7 cm-1), biodegradable nature, and appealing thermal and mechanical characteristic.

10103-57, Session 12

Gas spectroscopy system with 245 GHz transmitter and receiver in SiGe BiCMOS

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The implementation of integrated mm-wave transmitter (TX) and receiver (RX) in SiGe BiCMOS or CMOS technology offers a path towards a compact and low cost system for gas spectroscopy. Previously, we have demonstrated TXs and RXs for spectroscopy at 238 -252 GHz and 495 - 497 GHz using external phase-locked loops (PLLs) with signal generators for the reference frequency ramps. Here, we present a more compact system by using two external Fractional N PLLs allowing fast frequency ramps for the TX and RX, and for TX with superimposed frequency shift keying (FSK) or reference frequency modulation realized by an arbitrary waveform generator. The 1.9 m folded gas absorption cell, the vacuum pumps, as well as the TX and RX are placed on a portable breadboard with dimensions of 75 cm x 45 cm. The system performance is evaluated by high-resolution absorption spectra of gaseous methanol at 13 Pa for 241 - 242 GHz. The 2f (second harmonic) content of the absorption spectrum of the methanol

was obtained by detecting the IF power of RX using a diode power sensor connected to a lock-in amplifier. The reference frequency modulation reveals a higher SNR (signal-noise-ratio) of 98 within 32 s acquisition compared to 59 for FSK. The setup allows for jumping to preselected frequency regions according to the spectral signature thus reducing the acquisition time by up to one order of magnitude. We will develop the system for a frequency span of about 50 GHz, and apply software lock-in detection.

10103-58, Session 12

A metamaterial-coupled hot-electron-bolometer working at THz frequencies

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Superconducting materials are opening new opportunities in photonics for applications ranging from low loss plasmonic waveguides to metamaterials.

Here we focused our study on phonon cooled superconducting hot electron bolometers (HEBs) fabricated with ultra thin NbN film (4-5 nm). We studied a novel type of HEB metamaterial based (MM-HEB) optically coupled trough an array of split ring resonators acting as a resonant absorber at THz frequencies; we compared its performances with those of a conventional antenna coupled HEB.

The MM-HEB consists of a 2D array of split ring resonators designed to be resonant at 2.3, 2.4, 2.7, 2.9 THz with a single HEB (i.e., the NBN bridge) placed in the center of the metamaterial array and located in the central arm of one single split ring resonator.

We characterized the devices by electro optical measurements using as a sources both the black body emission and terahertz quantum cascade lasers (THz-QCLs).

We measured an optical responsivity of ~20 A/W for the MM-HEB. Measurements of Noise Equivalent Power (NEP) have been also performed and we got ~5pW/√Hz with a 1/f noise corner at 1 kHz. We measured the rise time of the HEBs using as source single pulses of a THz QCL emitting at 2.9 THz and we got pulse rise time around 250 ns limited by our electronic readout. The THz frequency response of the MM-HEB has been studied by using a FT-IR spectrometer , using both a QCL source and a globar source.

10103-59, Session 12

4x4 planar array antenna on indium phosphide substrate for 0.3-THz band application

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Recently, research of terahertz (THz) waves at frequencies from 100 GHz to 10 THz has attracted much attention. In basic THz broadband wireless communications, photodiode and Schottky barrier diode based on indium phosphide (InP) substrate converted the optical beat signal into sub-mm-waves by photomixing. In transceivers, high gain, small size and planar array antenna should be needed. In this paper, we present a novel design of a 0.3 THz-band 1 x 4 planar array antenna using four one-sided directional slot dipole antenna elements fed by branched coplanar wage guide (CPW) on the InP substrate. Each array antenna is connected to photo mixer. Moreover, four array antennas are placed on parallel. So, total number of antenna element is 16. By optimizing the length of floating metal layer, one-sided directional radiation can be realized. The total antenna size is 1,930 um x 1,930 um x 18 um. In order to increase the gain of forward direction, director metal layer is placed over 100 um air gap from top metal layer. At 0.3 THz, simulated realized gain in peak direction is 13.38 dBi and the full width at half maximum is 22.9 degree.

10103-60, Session 13

Terahertz monolithic solution for biosensing applications *(Invited Paper)*

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Silicon technology has been a great platform to explore the terahertz spectrum, by making accessible integrated terahertz equipment to the scientific community. CMOS technology is one of the most accessible platforms, but devices are still limited by the cutoff frequency. However, novel circuit design techniques have made it possible to build entire terahertz systems operating well beyond the device speed limits. In this paper, we will discuss the latest research innovations that led to the implementation of monolithically-integrated terahertz systems targeting biosensing applications.

10103-61, Session 13

Mechanically robust cylindrical metal terahertz waveguides for cryogenic applications

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As the ambition behind THz quantum cascade laser based applications continues to grow, abandoning free-space optics in favour of waveguided systems promises major improvements in targeted, easy to align and robust radiation delivery. This is especially true in cryogenic environments, where illumination is traditionally challenging. Although the field of THz waveguides is rapidly developing, most designs have limitations in terms of mechanical stability at low temperatures, and are costly and complicated to fabricate to lengths > 1 m. In this work, we investigate readily available cylindrical metal waveguides which are suitable for effective power delivery in cryogenic environments, and explore the optimal dimensions and materials available in terms of transmission losses, mode profiles, and bending losses. The materials chosen were extruded un-annealed and annealed copper, as well as stainless steel, with bore diameters of 1.75, 2.5, and 4.6 mm. Measurements were performed at three different frequencies – 2.0, 2.85 and 3.2 THz, with optimal transmission losses < 3 dB/m demonstrated at 2.0 THz, and bending losses as low as 2 dB/m at 90o. The potential for single mode, Gaussian-like TE11 transmission is also observed, which is favourable for most applications. Where appropriate, the effect of surface morphology on transmission losses has also been investigated, with significant variations in surface parameters evident for different material choices. This work is the first comprehensive investigation of cryogenically compatible THz waveguides, and paves the way for a new generation of systems to utilise THz QCLs for a whole host of low-temperature investigations.

10103-62, Session 13

THz wave generation through 2nd order non-linear excitonic effects in GaAs/AlAs MQWs at room temperature

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We report the second-order non-linear generation of THz radiation in GaAs/AlAs multi-quantum wells (MQWs), using continuous wave laser diodes at room temperature. A conversion efficiency of 1.2?10-5 was obtained without the use of plasmonic effects, nor any kind of an antenna or an applied E-field to the structure

A GaAs/AlAs MQW sample was designed to have excitonic resonances accessible by commercially available high power lasers (~850nm), and have E1HH1–E1LH1 splitting of 9.1meV (2.2THz). The sample was grown by MBE on n+ (100) GaAs with the MQW region containing 30 repeats of 11.9nm GaAs separated by 7.1nm AlAs barriers, sandwiched between 1500nm of n-doped and p-doped Al0.4Ga0.6As cladding, capped with 200nm p+ GaAs.

Whilst this structure lends itself to the application of a bias, preliminary measurements were carried out on a sample where the substrate and cap layer were removed. This sample was capillary bonded to a diamond heat spreader. Two collimated high lasers were used to simultaneously excite the E1HH1 and E1LH1 excitonic resonances. THz detection was made on the same axis as the excitation. A hemispherical silicon lens and long-pass filter ensured that all excitation laser light was extinguished, and only signals of wavelength >20um were detected. Clear THz signals were observed with co-linear polarization as compared to crossed-polarisation. Power dependent measurements confirmed that the signal was generated through a second order process.

Photocurrent measurements and simulations suggest that biasing the sample will enable tunable THz emission from 2.2-6THz

10103-63, Session 13

A Sensitive Coupling Structure for Terahertz Detectors Array

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Highly efficient microbolometer is of great importance in terahertz regime. Here we design the diffractive microlens with gold reflector in Nb5N6 microbolometer to improve the coupling efficiency of this THz detector. The diffractive microlens which consists of five square silicon staircases is designed on the back side of the high resistivity silicon wafer. The simulation results show the diffractive lens has a good ability of focusing at 0.65 THz and around, and thus it can improve the coupling efficiency of the incident power into the Nb5N6 microbolometers. Besides, a gold layer deposited on the surface of the diffractive microlens is used as a reflector. On the front side of the substrate, the deposited gold grating is used to reduce the reflection of incident signal. Through the gold layer and the diffractive microlens, the incident signal can be diffracted and enhanced on the center surface of the substrate where microbolometer can be fabricated on. In this central surface, the electric field of THz signal can reach up to 6 factor enhancement, and its energy is over 16 times higher than the situation of bare wafer. Thus, it is the diffracted signal can be coupled by the detector that results in higher detecting efficiency.

10103-64, Session 14

Waveguide development using wafer fused GaP/GaAs in THz quantum cascade lasers

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Two major waveguide designs have been demonstrated and widely used in THz quantum cascade lasers (TQCLs), Semi-insulating-surface-plasmon (SISP) and Metal-Metal (MM). SISP shows better mode quality but worse temperature performance. In this waveguide, the mode extends into the substrate because the bottom doping layer is thinner than its skin depth and its refractive index is slightly higher than the active region. As a result, the mode confinement fact is significantly reduced. Therefore, seeking a lower refractive index material to replace GaAs substrate is expected to increase confinement factor.

GaP has lower refractive index than GaAs at THz frequency range. At 2.7THz, the refractive index of GaP is 3.358 and that of GaAs is 3.625. This makes GaP a good candidate as substrate materials of THz QCLs. However, it is difficult to grow GaAs/AlGaAs material using Molecular Beam Epitaxy technology on GaP substrate due to large lattice mismatch. Here, a direct wafer fusion technique was developed to achieve GaP/GaAs interface THz QCL structure. First, mode simulation at 2.6 THz was carried out using COMSOL to analyze the confinement factor and waveguide losses of several GaP/GaAs fused structures. The results showed promising increase of confinement factor but also higher losses. Second, devices were fabricated and tested between 2.5 THz- 2.9 THz, showing good electrical characteristics but poor optical performance, which is mainly due to the degradation of crystal quality after high temperature fusion process. Therefore, a low temperature fusion process, such as SOG is necessary to fabricate GaP/GaAs THz waveguide.

10103-65, Session 14

Printing sub-THz wire grid polarizers using a composite liquid metal ink

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A low-cost method to inkjet print terahertz polarizers is presented. A liquid metal printer is used to deliver an eutectic Gallium and Indium alloy (EGaIn24.5) onto vynil acetate film substrates to create flexible wire grid polarizers (10 x 20 mm) in the sub-THz band with a nominal spacing of 100 and 200 ?m, respectively.

A Terahertz Time Domain Spectroscopy (THz-TDS) setup has been used to characterize the polarizers. The experimental results have been compared with FDTD simulations (CST Studio) showing good agreement. The characterization of the polarizers shows an extinction ratio up to 14 dB in the 0.1-0.7 THz and low loss (< 1 dB). A microscopic characterization of the polarizers shows a variance in the line spacing of about 9%.

This new fabrication method allows a quick and cost-effective approach for the development of sub-THz polarizers to be used in polarization-resolved spectroscopy, polarimetric quality monitoring sensors and the characterization of THz components. Additionally, the fabrication method can be extended to print other passive components such as filters.

10103-66, Session 14

Graphene-based plasma wave interconnects for terahertz band communication

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In this work, we present physics-based performance models of a plasmonic transistor that

exploits Dyakonov-Shur instability to electrically excite terahertz plasma waves in a quasi-ballistic (QB) channel material such as GaN or GaAs [1-3]. We use multi-layer graphene as the gate electrode material in the plasmonic transistor. Owing to its complex dynamical conductivity, the plasma waves in the QB channel are reflected as transverse magnetic surface plasmon polaritons (SPPs) in graphene [4-5]. The plasma waves generated in graphene can be guided either to another plasmonic transistor for local data communication up to 10's of microns, or they can also be directed toward another radiating structure such as graphene-based nano antennas for wireless communication at the global interconnect level [6]. The frequency response of the device will be obtained by jointly solving the hydrodynamic equations in the plasmonic transistor and Maxwell's equations in graphene. We will incorporate plasmon-damping mechanisms due to intrinsic phonons, impurities in graphene, and edge roughness in scaled graphene ribbons. The effects of process parameters on the plasmon lifetime will be captured in the conductivity of graphene obtained within the Kubo formalism [7] by ignoring non-local effects. We identify the optimal design and efficiency of the plasmonic transistor tuned for a specific resonant frequency. We also compute the performance metrics – latency and energy-per-bit – of the plasmonic waveguide and compare them against their conventional Cu/low-? counterparts. The impact of the number of layers in graphene and their coupling on the excitation efficiency of the plasmonic transistor is also studied.

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10103-67, Session 14

A broadband ultrathin metamaterial absorber using tilted parallel strips

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Metamaterials have attracted the attention of many researchers emanating from their interdisciplinary applications in electromagnetics, optics, nanoelectronics and biomedical devices ranging from low microwave to visible wavelengths. This attractive terminology refers to three dimensional periodic engineered artificial composites made of natural materials but brings out unique properties beyond those of conventional materials. Since metamaterials experimentally suffer from high loss, their counterpart two dimensional structure known as metasurfaces has become an alternative structure to overcome this drawback while offering the same advantages and properties. Interestingly, the absorption loss in metadevices led to the concepts of ultra-lightweight and ultrathin absorbers in comparison with their traditional counterparts. These are great candidates for sensing, solar cells and imaging.

In this paper, a polarization insensitive metamaterial absorber is proposed consisting of a dielectric layer sandwiched between two rotated parallel metallic strips and ground plane. First, a new analytical model is introduced to predict the absorption frequency for square, rectangular and wire geometries which shows less relative errors in comparison with previous proposed models. Then, ultra wide bandwidth absorption covering the entire x-band and Ku-band restricting a 10-dB absorption bandwidth is achieved with a relative material thickness ?_0/10 and a relative FWHM absorption bandwidth of 90% for normal incident angle. The model also shows good absorption coefficients for oblique incident angles for both s- and p-polarizations. Three different resonance modes are observed, which led to such broadband absorption. Each resonance mode is investigated to determine their dependence on the scatters and unit cell dimensions, which can help one to design a multiple band absorber. The electromagnetic field distributions of the scatters are studied to explain the absorber mechanism. The results are compared to the previous works that present remarkable improvement.

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SPIE. PHOTONICS WEST OPTO

10104-1, Session 1

Recent progress in HVPE-GaN growth *(Invited Paper)*

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Growth of high structural quality and high-purity thick HVPE-GaN layers on 1-, 1.5-, and 2-inch native substrates will be described in detail in this paper. Topics like doping, re-growth, and wafering will be also presented. Electronic and optoelectronic devices based on free-standing (F-S) HVPE-GaN substrates will be demonstrated. It will be shown that there are two limiting factors of the HVPE growth method: parasitic deposition and anisotropy of the growth. Both of them lead to formation of defects in the growing crystals. Therefore, crystallization time is strongly limited and despite a very high growth rate in HVPE process, this technology remains today a 'wafer to wafer' technology. Parasitic deposition is not as crucial as the anisotropy of the growth and growth in lateral directions. The latter seems to be today the main challenge for HVPE-GaN growth regardless of the used seed. This means that engaging lattice constant engineering is inevitable. The same growth rate and above all the same lattice constants of GaN grown in the c-direction and lateral directions seem to be crucial. Without ensuring a stable growth in the growth direction and without a full control of incorporation of dopants, and hence the lattice constants, in all growth directions, crystallization of real bulk GaN will be difficult to achieve. It will be strongly discussed in this paper.

10104-2, Session 1

Recent progress of high-quality GaN substrates by HVPE method *(Invited Paper)*

Hajime Fujikura, Takehiro Yoshida, Masatomo Shibata, Yohei Otoki, SCIOCS (Japan)

Recently, use of GaN substrates grown by HVPE method for opto-devices and electronic devices, such as LDs, high performance LEDs, power switching devices and RF power devices, have been widely spread in mass production and developments. The HVPE growth technology for the stable production with high quality and the excellent device performances by using the GaN substrates are shown here. For the further improvement of the performance and the cost, these substrates are being required to have more better quality, lower price and larger wafer size. The recent progressed technology to achieve these requirements will be also introduced. We'll show the basic technology of free standing HVPE method, named VAS (Void Assisted Separation) method to obtain the low defects density crystal with stable production. We also demonstrate the results of how much the performance of electrical devices, such as breakdown voltage of HEMTs and PN diode and RF performance of HEMT, are improved by using this high quality GaN substrates. The recent HVPE technology to achieve very low defects, high purity and large diameter of 100mm and 150mm are introduced.

10104-3, Session 1

Semi-insulating HVPE-GaN grown on native seeds

Michal Bockowski, Institute of High Pressure Physics (Poland)

Hydride Vapor Phase Epitaxy (HVPE) is the most popular method for fabrication of high structural quality and high-purity GaN substrates. The technology of obtaining a low level of impurities together with high crystallographic quality of HVPE-GaN crystals enables the next step, namely introducing intentional doping to the growth process and obtaining semi-insulating crystals. This work describes developing a method for incorporation of acceptors (carbon or iron) into HVPE-grown GaN while maintaining high structural quality and low level of other impurities in the material. Ammonothermally grown GaN crystals and substrates will be used as seeds. All growth processes will be carried out in a home-built quartz horizontal HVPE reactor. Methane (CH4) will be used as the precursor of carbon. The FeCl2 precursor will be created inside the reactor chamber by an HCl-stream over elemental iron. HVPE crystallization runs with different flows of acceptor precursors will be performed. HVPE-GaN:C and HVPE-GaN:Fe crystals will be characterized with X-ray diffraction, Raman spectroscopy, low-temperature photoluminescence, optical as well as transmission electron microscopies, Hall measurements, and Secondary Ion Mass Spectrometry. The properties of crystallized HVPE-GaN:C and HVPE-GaN:Fe will be compared in detail. It will be shown that concentrations of impurities (carbon or iron) in the new-grown material is always very uniform across the (0001) surface and along the c-direction. This result together with a high crystalline quality of the crystallized material will allow to obtain the semi-insulating HVPE-GaN crystals with resistivity of the order of 109 ?.cm at room temperature.

10104-4, Session 1

Ultraviolet microcavity light-emitting diode with ion-implanted current aperture

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Vertical-cavity surface-emitting lasers (VCSELs) are known to have advantages of lower threshold current operation, circular and low-divergence output beam, and lower temperature sensitivity compared to edge-emitting laser diodes. In conventional VCSELs, the formation of a current aperture plays a vital role in the device characteristics. Low laser thresholds and single-transverse-mode operation would not be possible without a well-defined current aperture to confine carriers to generate photons between the two distributed Bragg reflectors. Since the introduction of the controlled oxidation process for the AlxGa1-xAs material system by Dallesasse and Holonyak in 1989, most VCSELs have employed oxidation for current aperture formation as well as optical confinement and this technique has become one of the most commonly used fabrication techniques for traditional III-V compound semiconductor infrared VCSELs. However, for III-N emitters operating at wavelengths in the ultraviolet to green wavelength range, the formation of Al-based native oxide layers has not proven feasible. As a result, various current-confinement techniques have been studied such as, selective-area growth of buried AlN, oxidizing AlInN, and selective activation of acceptors.

In this work, we report an ion-implantation process which is effective for carrier confinement and defines a current aperture for our III-N ultraviolet microcavity light-emitting diodes (MCLEDs). The devices have peak emission wavelength of ~371.4 nm with the spectral linewidth of 5.1 nm at the highest pulsed current injection level of 15 kA/cm2. Further discussion on the material growth, material characterization, implantation parameters, as well as numerical simulation for structural design will be presented in the conference.

10104-5, Session 2

Development of high-quality semi-polar GaN for long wavelength emitters *(Invited Paper)*

Tao Wang, The Univ. of Sheffield (United Kingdom)

Current GaN technology on c-plane sapphire has approached its limits and thus the performance of GaN-based optoelectronics which has been predicted to be a 10s of Billion US dollar market in the very near future cannot be further improved, while both theoretical and experimental work suggests that semi-polar GaN is the only solution to break through the bottle-neck. Semi-polar GaN, in particular, (11-22) GaN, is becoming increasingly important due to its advantages of reducing the spontaneous and piezoelectric polarizations and exhibiting higher indium incorporation efficiency than either non-polar or polar surface. This makes (11-22) semi-polar GaN be particularly important for achieving longer emission wavelength such as green and yellow emitters that have found wide applications in fabrication of phosphor-free white lighting sources, ultra-fast visible light communications (Li-Fi), polarized backlighting, and opto-genetics. However, due to the lack of suitable substrates, semi-polar (11-22) GaN on industry-preferred substrates, such as sapphire, contains a high density of defects, including basal stacking faults (BSFs) and associated partial dislocations. In order to address this material challenge, our group has successfully obtained (11-22) GaN with significantly improved crystal quality on 2 inch sapphire by developing a cost-effective overgrowth approach on regularly-arrayed micro-rods, where the diameter, shape and orientation of micro-rods can be accurately controlled. In this presentation, I will demonstrate high crystal quality (11-22) GaN/InGaN LEDs overgrown on such GaN templates, emitting strong green, yellow, yellow-green and amber emission. All the emission demonstrate clear polarized features. The mechanisms of the overgrowth and defect reduction will be explored.

10104-6, Session 2

Basic characteristics of GaN prepared by pulsed sputtering deposition

Kohei Ueno, Atsushi Kobayashi, Jitsuo Ohta, The Univ. of Tokyo (Japan); Hiroshi Fujioka, The Univ. of Tokyo (Japan) and ACCEL Embodied Media Project Japan Science and Technology Agency (Japan)

Basic characteristics of GaN films prepared by pulsed sputtering deposition (PSD) at low substrate temperatures have been investigated. The dominant peak in the low temperature photoluminescence spectrum of PSD uid-GaN are originated from free excitons. Althogh the electrical property of uid-GaN is either semi-insulating or slight n-type depending on the situation of compensation, PSD-GaN can be doped into p-type or n-type by introduction of Mg atoms or Si atoms. The highest room temperature mobilities for n-type GaN and p-type GaN are 1000 cm2/Vs and 34 cm2/Vs, respectively. These results indicate that PSD-GaN has low background impurity levels and can be used for various device applications. Basic characteristics of HEMTs, MISFETs, LEDs, and solar cells fabricated with PSD will be discussed in the presentation.

10104-7, Session 2

Predicted lattice-misfit stresses in a gallium-nitride (GaN) film

Ephraim Suhir, ERS Co. (United States) and Portland State Univ. (United States); Sung Yi, Portland State Univ. (United States) and ERS Co. (United States)

A simple and physically meaningful theory-of-elasticity based predictive model is developed for the evaluation of the lattice-misfit stresses in a gallium-nitride (GaN) film grown on a circular substrate (wafer). Normal radial and circumferential stresses acting in the film cross-sections and interfacial shearing and peeling stresses are considered. It is shown particularly that while the normal stresses in the semiconductor film are independent of its thickness, the interfacial shearing stresses increase with an increase in the induced force (not stress!) acting in the film cross-sections, and that this force increases with an increase in the film thickness. This leads, for a thick enough film, to the occurrence, growth and propagation of dislocations. These start at the assembly ends and propagate, when the film thickness increases, inwards the structure. The following major problems are addressed and discussed:

1. The normal stresses in the film mid-portion are not affected by the circular configuration nor by the bow of the assembly, as long as the substrate diameter is large enough.

2. The interfacial shearing stress can be evaluated from the basic equation without considering its coupling with the peeling stress and is governed by the magnitude of the parameter of the interfacial shearing stress that is determined by the axial compliance and Poisson's ratio of the film and the interfacial compliance of the assembly. The latter is affected by both the film and the substrate material properties and thicknesses. The above basic equation is of Bessel type and its solution is expressed through the modified Bessel function of the first kind of the first order. This solution enables one to obtain the following simple formula for the interfacial shearing stress: where is the maximum value of this stress, is the ratio of the lattice constants of the substrate ( ) and the film ( ), and the function considers the effect of the product of the parameter of the interfacial shearing stress and the assembly size (radius) . The obtained formulas indicate that the maximum interfacial shearing stress at the assembly edge increases with an increase in the effective Young's modulus of the film material, with an increase in the parameter , in the thickness of the film, and in the lattice misfit that plays the role of the external loading. The lattice mismatch stress is inversely proportional to the in-plane compliance of the film. The radial and the tangential normal stresses in the film are expressed as follows:

,

Here is the normal (radial and circumferential) stress in the film in its mid-portion. The expressions in the brackets are, in effect, "corrections" that consider the role of the finite radius of the assembly. In the case of a large size (large) and/or stiff (large k) assemblies, the obtained formulas yield:

, .

These formulas indicate that the normal stresses, and , in the film are uniformly distributed over its inner portion ( ); the radial stress is zero at the assembly end; and the circumferential stress at the assembly boundary is, i.e., by the factor of higher than the normal stresses, , in the mid-portion of the film. The general concepts and analytical results will be illustrated in the full-length paper by a detailed numerical example. The following major conclusions are drawn from the carried out analysis: 1) The peripheral shearing and circumferential normal stresses are significant; 2)

The dislocations in the film occur first, because of the elevated shearing stresses, at its peripheral portions and then propagate inwards the assembly, until the stress relief becomes sufficient to arrest the further propagation of dislocations; 3) Simple formulas can be used to evaluate the maximum lattice mismatch stresses in a bi-material circular semiconductor thin film assembly. Here is the maximum normal radial and normal circumferential (tangential) stress in the film's mid-portion, is the lattice-misfit strain (the film is in compression, if the strain is positive), is the maximum interfacial shearing stress at the assembly end, is the parameter of the interfacial shearing stress, is the film thickness, and is the maximum normal circumferential stress at the assembly end; 4) The developed predictive model can be used for the assessment of the merits and shortcomings of a particular semiconductor-crystal growth technology (not necessarily GaN one) before the actual experimentation and/or fabrication is considered and conducted. The models can be used particularly to determine, from the observed critical film thickness, the material, design and technological factors that lead to elevated dislocation densities.

Additional information could be found in the publications:

1. E. Suhir, "Stresses in bi-metal thermostats", ASME J. of Applied Mechanics, vol.55, No.4, 1986.

2. S. Luryi, E. Suhir, "New approach to the high quality epitaxial growth of lattice-mismatched materials", Applied Physics Letters, vol.49, No. 140, 1986

3. E. Suhir, "An Approximate Analysis of Stresses in Multilayer Elastic Thin Films", ASME Journal of Applied Mechanics, vol. 55, No. 3, 1988.

4. E. Suhir, "Stresses in Bi-Material GaN Assemblies", Journal of Applied Physics, 110, 2011

5. E. Suhir, "Lattice-Misfit Stresses in a Circular Bi-Material Gallium-Nitride Assembly", ASME J. Appl. Mech., vol.80, January 2013

6. E. Suhir, "Predicted Thermal and Lattice-Mismatch Stresses", in T. Nishinaga and T.F.Kuech, eds., "Handbook of Crystal Growth", 2e, vol.3, , Elsevier, 2015

10104-8, Session 3

Carrier dynamics studies of III-nitride materials using photo-acoustic and photoluminescence measurements *(Invited Paper)*

Atsushi A. Yamaguchi, Takashi Nakano, Shigeta Sakai, Haruki Fukada, Kanazawa Institute of Technology (Japan); Yuya Kanitani, Shigetaka Tomiya, Sony Corp. (Japan)

Internal quantum efficiency (IQE) in III-nitride materials is usually estimated from temperature dependence of photoluminescence (PL) intensity by assuming that IQE at cryogenic temperature is unity. III-nitride samples, however, usually have large density of non-radiative defects, and the assumption is not necessarily valid. Photo-acoustic (PA) measurement is a good method to directly detect the heat generation by non-radiative recombination, and can be a complementary approach to reveal the recombination processes. Last year, we developed a new method to estimate accurate IQE values by simultaneous PA/PL measurements. The IQE values can be estimated by analyzing the correlation between PA and PL signals in nonlinear behavior of their excitation-power dependence, by considering that these signals are proportional to the amounts of heat and light generation in the non-radiative and radiative recombination, respectively. In this study, we have applied the method to InGaN quantum-well active layers and have measured the IQE values and their excitation carrier-density dependence in the layers. Also, we have performed temperature-dependent time-resolved measurements for the same samples, which enable us to accurately estimate the radiative and non-radiative lifetimes of photo-excited carriers by the combination with the PA/PL simultaneous measurements. Finally, we will discuss the carrier dynamics in the InGaN quantum-well layers and their temperature dependence.

10104-9, Session 3

Nanoscale cathodoluminescence of In-rich InGaN layers on top of InGaN compositional grades

Gordon Schmidt, Otto-von-Guericke-Univ. Magdeburg (Germany); Max Trippel, Otto-von-Guericke Univ. Magdeburg (Germany); Peter Veit, Frank Bertram, Otto-von-Guericke-Univ. Magdeburg (Germany); Karine Hestroffer, Univ, of California, Santa Barbara (United States); Cory C. Lund, Haoran Li, Stacia Keller, Umesh K. Mishra, Univ. of California, Santa Barbara (United States); Jürgen H. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

Nowadays, the realization of high In content InGaN alloys is still limited by their material properties. Nevertheless, due to the lower thermal dissociation the growth of N-polar InGaN is a promising approach to incorporate more indium compared to Ga-polar films, which opens the possibility of realizing high In-content InGaN layers.

Using cathodoluminescence spectroscopy performed in a scanning transmission electron microscope (STEM-CL), we analyze the optical properties of an N-polar In0.2Ga0.8N layer on top of an InxGa1-xN grading layer. The structure was grown by plasma-assisted molecular beam epitaxy on an N-polar MOVPE-GaN/sapphire template. For the adjustment of the lattice constant of the top In0.2Ga0.8N layer a gradient layer was grown. The In composition was ramped from 2 % to 20 % towards the top of the InxGa1-xN grade.

STEM images exhibit a homogeneous contrast for the first 100 nm of the InxGa1-xN gradient. Beyond, the gradient layer becomes inhomogeneous culminating in nanorod formation above 400 nm InxGa1-xN. Despite the 3D growth of the gradient layer, the topmost InGaN layer grows laterally resulting in a partially coalesced and contiguous layer.

The correlation of the STEM images with monochromatic CL intensity images reveals a red shift from 400 nm to 580 nm towards the top of the InGaN gradient layer due to the compositional gradient as well as relaxation process. The coalesced InxGa1-xN layer emits luminescence contributions well above 550 nm. Multiple InGaN peaks arise at the same position in the gradient as well as InGaN layer demonstrating the different local In incorporation.

10104-10, Session 3

Facet temperature measurement of GaN-based laser diodes using thermoreflectance spectroscopy

Dorota Pierscinska, Kamil Pierscinski, Institute of Electron Technology (Poland); Lucja Marona, Przemyslaw Wisniewski, Piotr Perlin, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland); Maciej Bugajski, Institute of Electron Technology (Poland)

Investigation of temperature distribution on the facet of the device, with high spatial and temperature resolution, is crucial to gain insight into thermally activated degradation modes in GaN-based lasers. This work undertakes the problem of temperature distribution measurement on the facet of the nitride lasers.

Thermal investigation of the nitride devices is mainly based on thermal imaging. However, this approach is characterized by inherently low spatial resolution, as well as the fact, that the registered image, is averaged over the volume of the device, limiting the ability to observe the enhanced thermal processes occurring at the vicinity of the surface (front facet). Thermoreflectance spectroscopy, provides the possibility of registering of high spatial and temperature resolution images of the surface of the device operating in quasi-CW or pulsed mode.

In this work we present development of the unique experimental setup and procedure, devoted to the thermal characterization of the nitride lasers. Thermal characterization of series of devices was performed, providing a mode for comparing different operating conditions, geometries and device designs. Measurement of the temperature profile and high-resolution temperature distribution maps on the front facet of AlGaN/GaN via thermoreflectance spectroscopy will be demonstrated. The results indicate the direction to take in order to improve the laser reliability and performance. Additionally, the degradation mechanisms induced by temperature increase are discussed.

10104-11, Session 4

Intersubband transitions in the THz using GaN quantum wells *(Invited Paper)*

Caroline B. Lim, CEA Grenoble (France); Akhil Ajay, CEA-Grenoble (France); Catherine Bougerol, Institut NÉEL

(France); Jörg Schörmann, Justus-Liebig-Univ. Giessen (Germany); David A. Browne, Mark Beeler, Eva Monroy, CEA Grenoble (France)

Research on III-nitride intersubband (ISB) transitions in the THz spectral range is motivated by the large LO-phonon energy of GaN, which should permit device operation with limited thermal interference, and at infrared wavelengths inaccessible to other III-V compounds due to Reststrahlen absorption. A main challenge to extend the polar GaN-ISB technology towards the THz region comes from the polarization-induced internal electric field, which imposes an additional confinement that increases the energetic distance between the electronic levels. In order to surmount this constraint, we propose alternative multi-layer quantum well designs that create a pseudo-square potential profile with symmetric wavefunctions [1]. The robustness of these designs and their integration in device architectures requiring tunneling transport will be discussed.

An alternative approach to obtain square potential profiles is the use of nonpolar crystallographic orientations. In this contribution, we present an experimental study of THz ISB transitions in m-plane GaN/AlGaN quantum wells grown on free-standing m-GaN [2]. For Al contents below 15%, such structures can be grown without epitaxially-induced extended defects. We demonstrate nonpolar quantum wells which display ISB transitions in the 7?-10 THz band, and we will discuss the effect of the doping density in the quantum wells on the transition energy and line width. Finally, we will present a comparative study using silicon and germanium as n-type dopants.

[1] M. Beeler, et al., Appl. Phys. Lett. 105, 131106 (2014)

[2] C.B. Lim, et al., Nanotechnology 26, 435201 (2015); Nanotechnology 27, 145201 (2016).

10104-12, Session 4

Freezing of quantum confinement Stark effect at low temperatures?

Lucja Marona, Agata Bojarska, Grzegorz Staszczak, Institute of High Pressure Physics (Poland)

There are two physical phenomena governing the light emission in InGaN quantum structures: the internal electric fields and the In composition fluctuations. Both these effects manifest through the blue shift of the wavelength emission with the excitation intensity and both of them have the pronounced influence on the light emitting properties of these structures.

In order to discriminate between these two effects, we fabricated two identical structures: one with the quantum barriers doped with silicon (method for internal electric field screening) and the other with an undoped active region. Under the optical excitation the emission peak shifts by almost 35 nm (Si doped) and 50nm (without Si). Additionally, we studied temperature dependence of the emission peak position. In case of low temperatures and at RT and high pumping energy, emission energy position is almost the same for both samples. Our observations lead us to the conclusion that at low temperatures and at high pumping regime the Quantum Confined Stark Effect (QCSE) is totally suppressed. While this is understandable that at high carrier injection QCSE is screened, the origin of the low temperature effect is much less clear. We can speculate that at the lowest temperature the carriers are localized eliminating the spatial separation of holes and electrons wavefunctions.

Measured cathodoluminescence (CL) maps show the same level of the indium fluctuations for both samples. At higher excitation the fluctuations starts to be less visible suggesting band filling of states.

Finally we compare recombination times by means of time resolved photoluminescence.

10104-13, Session 4

Transport properties of AlInN/AlN/GaN heterostructures grown on silicon substrates

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Lattice-matched AlInN/GaN heterostructure is considered a promising candidate for power and RF device applications because of its stronger spontaneous polarization, which induces higher carrier concentration and lower channel resistance than its AlGaN/GaN counterpart. This study aims at growing high electron mobility and low channel resistance AlInN/GaN heterostructures on Si substrates by metal-organic chemical vapor deposition, and investigating the carrier scattering mechanisms in these heterostructures.

It is found that a binary spacer layer, i.e. AlN, inserted between the AlInN barrier and GaN channel layer effectively reduces alloy scattering and leads to a high electron mobility of 1,360 cm2/V?s with two-dimensional electron gas (2DEG) concentration of 2.13?1013 cm-2.

In general, 2DEG concentration increases with increasing the Al content of AlInN, while electron mobility decreases with increasing 2DEG density. It is found that the degradation of electron mobility with increasing 2DEG is more significant for the samples with a rough AlInN/AlN interface than those with a smooth one. Temperature-dependent Hall effect measurements indicate that the electron mobility of AlInN/AlN/GaN HEMTs with high 2DEG density is dominated by interface roughness scattering in addition to optical phonon scattering. Having a GaN cap layer on AlInN barrier, HEMTs with Rsh< 220 ohm/sq and electron mobility >1700 cm2/V-s are demonstrated on 6-inch silicon substrates

10104-14, Session 4

Investigation of the optical properties of dilute-As GaNAs semiconductors

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III-Nitride semiconductors like InGaN have been widely implemented in light emitting diode (LED) applications, attributed to the extensive understanding of the materials. In comparison to the InGaN alloy, dilute-anion GaN-based semiconductors are still at an early stage. Recent work identified dilute-As GaNAs alloys as the alternative III-Nitride semiconductors for use in visible light-emitting applications. Specifically, the investigation of electronic properties of dilute-As GaNAs led to the discovery of interband Auger process suppression – a known efficiency-limiting issue in InGaN LEDs. However, the literature on dilute-As GaNAs is still severely limited, including information related to the alloys' optical properties. Therefore, understanding the optical properties of the dilute-As GaNAs alloys is an important step towards developing the alloy for device applications.

In this work we present the optical properties of dilute-As GaNAs alloys with varying As-content up to 12.5%, by using Density Functional Theory (DFT) calculations. The optical properties such as the refractive index, reflectivity and dielectric function of dilute-As GaNAs alloys for each As-content are presented and discussed. The directionality effect in the refractive index changes of the III-Nitride alloys has been analyzed. In addition, the real and imaginary parts of the dielectric function for varying alloy compositions in the dilute-As GaNAs alloys are analyzed. Our analysis indicates significant changes in the optical properties when the Arsenic is incorporated into the GaN alloys. Further analysis has been extended into relevant dilute-anion GaN-based alloys, and the comparison of the optical properties of the alloys will be briefly discussed.

10104-15, Session 4

Long wavelength emission on relaxed InGaN substrates

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InGaN based LEDs are known to be very efficient in the blue range. However, although InGaN can theoretically cover all visible range, quantum efficiency drops when emission wavelength emission is increased due to quantum confined Stark effect. Furthermore, indium incorporation is hindered by compressive strain induced by lattice mismatch between InGaN and GaN. To tackle the lattice mismatch problem, a full InGaN structure on a relaxed InGaN substrate is proposed.

The structure consisting of five InxGa1-xN / InyGa1-yN multi quantum wells on top of an InyGa1-yN buffer layer is grown by MOVPE on an InGaNOs substrate from Soitec company. Three InGaNOs substrates of lattice parameters of 3.190, 3.200 and 3.205 Ångströms were co-loaded in order to compare their ability to incorporate indium for the same growth conditions. For reference, a sample grown on GaN template will allow us to compare the wavelength red-shift resulting of the use of InGaNOs template.

The samples were characterized by photoluminescence at room temperature using 375 nm and 405 nm laser diodes. It is shown that long wavelengths can be reached thanks to the use of InGaNOs substrates. For same active region growth conditions as reference sample, a red-shift up to 65 nm (from 445 to 510 nm) is observed, demonstrating InGaNOs potential for easier In incorporation. Using different growth conditions, wavelengths up to 600 nm have been reached. First internal quantum efficiency measurements demonstrate a good quality material. InGaNOs seems promising for emission in the "green gap"and beyond.

10104-72, Session 4

Temperature-dependent photoluminescence in InGaN/GaN blue laser diodes

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The InGaN/GaN laser diodes (LDs) have attracted much attention due to their wide applications in laser display and laser lighting. Temperature-dependent photoluminescence (TDPL) is an important characterization method used to investigate the luminous efficiency and internal quantum efficiency. In this study, the temperature and power-dependent photoluminescence in InGaN/GaN blue LDs is investigated. From the temperature-dependent PL spectra, we observed conventional "S-shaped" behavior of the peak wavelength, both "U-shaped" and "W-shaped" behavior of the linewidth. From the temperature and power-dependent photoluminescence results, the shoulders in the "W-shaped" linewidth disappear as the power density increases. We attributed the "W-shaped" behavior of the linewidth in our blue LDs to the saturable absorption centers in the quantum wells.

10104-16, Session 5

Design of Al-rich AlGaN quantum-well structures for efficient UV emitters *(Invited Paper)*

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AlGaN-based quantum wells (QWs) are quite promising for UV emitters because of the direct, wide band gap covering the 200-to-300 nm spectral range. The crystal growth technology has been improved, but the external quantum efficiency of AlGaN-based LEDs is still below 20%. To achieve a higher efficiency, there are many factors to solve. We like to discuss some of them with a particular focus on the radiative and nonradiative recombination processes.

One of the nonradiative recombination centers is point defects most likely due to Al vacancies. Low temperature cathodoluminescence images show dark spots due to threading dislocations. However, the dark spots disappear at room temperature. These experimental results can be accounted for by considering that excited carriers are captured by point defects before reaching threading dislocations. Therefore, to improve efficiency, reducing point defects is more important than reducing threading dislocations.

Another possible nonradiative recombination center is misfit dislocations. Although quite thick critical layer thicknesses (CLT) for the lattice relaxation between an AlGaN film on AlN (0001) have been reported using x-ray diffraction measurements, our time-resolved photoluminescence (TRPL) indicates a much thinner CLT. This discrepancy is caused by characteristics of the measurements; TRPL sensitively detects nonradiative recombination of carriers at misfit dislocations, while x-ray diffraction assesses macroscopic strain distribution. Based on the TRPL results, the use of AlGaN buffer layers beneath AlGaN QWs is proposed.

For radiative processes, our experimental studies suggest that semipolar QWs as well as lower dimensional quantum structures such as quantum wires effectively enhance the recombination rates.

10104-17, Session 5

AlGaN-based metal-semiconductor-metal photodetectors with high external quantum efficiency at low operating voltages *(Invited Paper)*

Moritz Brendel, Sebastian Walde, Ferdinand-Braun-Institut (Germany); Markus Helbling, Ferdinand-Braun-Institut (Germany); Arne Knauer, Sylvia Hagedorn, Frank Brunner, Viola Kueller, Andrea Knigge, Markus Weyers, Ferdinand-Braun-Institut (Germany)

AlGaN-based photodetectors (PD) with high external quantum efficiency (EQE) at low voltage have great potential for monitoring ultraviolet light sources and are requested for various applications like, e.g., gas sensing, curing of coatings, phototherapy, or water disinfection. Schottky PDs with a (semi-)transparent electrode or more complex p-i-n-based PD structures work at zero bias but both generally suffer from issues concerning sufficient doping and processing of ohmic contacts. In contrast, the metal-semiconductor-metal (MSM) PD does not require doping and ohmic contacts and thus is easy to fabricate, but usually has no zero-bias operation mode.

We present a comprehensive study of experimental and simulated results on solar-blind Al0.5Ga0.5N/AlN MSM PDs comparing different illumination conditions, electrode configuration and epitaxial structures. For bottom-illuminated PDs a threshold and saturation of the EQE at values of up to 0.68 is observed depending on bias voltage and AlGaN layer thickness. According to the analysis of two-dimensional drift-diffusion-based

calculations this behavior is related to the accumulation of photogenerated holes within the polarization-induced space charge region at the AlGaN/AlN heterointerface. The role of growth-related contaminations at this interface will also be discussed.

Standard devices with only 100 nm thick AlGaN absorber already show high EQE values of up to 0.3 at about 7 V. With asymmetric electrode configuration (different electrode widths), bottom-illuminated MSM PDs have an EQE of 0.3 already at about 1 V. Using two different contact metals (ohmic and Schottky type) finally enables the operation at zero bias with EQE of 0.24.

10104-18, Session 5

Sub-250nm deep-UV AlGaN/AlN distributed Bragg reflectors

Theeradetch Detchprohm, Young-Jae Park, Yuh-Shiuan Liu, Karan Mehta, Georgia Institute of Technology (United States); Shuo Wang, Arizona State Univ. (United States); Tsung-Ting Kao, Shyh-Chiang Shen, Douglas Yoder, Georgia Institute of Technology (United States); Fernando A. Ponce, Arizona State Univ. (United States); Russell D. Dupuis, Georgia Institute of Technology (United States)

AlGaN/AlN DBR structures were grown on 1.5 ?m-thick AlN templates on 2-inch diameter (0001) sapphire substrates using an AIXTRON 3?2" Close-Coupled Showerhead MOCVD reactor. The threading dislocation density of the AlN templates used in this work was typically in the lower 109 cm-2 range. The epitaxial process consisted of 100nm AlN grown with growth rate of 2.4 ?m/h at 1130°C followed by pairs of layers of AlGaN and AlN which were grown to their designed thickness matching an optical quarter wavelength of the target reflection center wavelength. Both sets of layers were grown under 100 mbar at 1130°C. In order to minimize the composition pulling effect, each AlGaN layer was grown as a short-period superlattice (SPSL) structure of AlGaN and AlN with average growth rate of 0.20-0.22 nm/s. No cracking was observed even for the total pair number of 50. Thus, no lattice strain management layer was necessary for any DBR structure reported here. All samples appeared smooth as confirmed by differential interference phase contrast optical microscopy up to magnification of 500. The reflectivity peaks were located just before the absorption from the AlGaN layers became dominant. The peak reflectivity values as calibrated by a certified UV enhance Al mirror were 99.5% at ?center = 226 nm and 100.0% at ?center = 247 nm for a (SPSL-Al0.87Ga0.13N)/AlN DBR, and (SPSL-Al0.73Ga0.27N)/AlN DBR, respectively. More details about the MOCVD process, DBR design, material characterization including TEM, and optical excitation of deep UV AlGaN MQWs will be presented.

10104-19, Session 5

Evaluation of intervalley energy of GaN conduction band by ultrafast pump-probe spectroscopy

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The energy difference between the lowest conduction band valleys is a fundamental semiconductor parameter affecting performance of electronic devices via intervalley electron scattering. Surprisingly, the intervalley energy (IVE) value in GaN is still disputed. Recent photoemission experiments showed that IVE is 0.90 – 0.95 eV, which is considerably smaller than the >2 eV values obtained by ab initio calculations.

One of the suitable techniques to measure IVE is time-resolved spectroscopy. Excitation wavelength dependent photoluminescence and pump-probe transients allow pinpointing the onset of the intervalley scattering by increase of the electron relaxation time towards the bottom of the conduction band. In this work, we apply this approach by performing differential transmission (DT) and reflection (DR) measurements on n-GaN crystal. In DR, ultraviolet (UV) pump creates electrons in the ? valley at energies around the scattering threshold, and the onset energy is determined by the change of the electron relaxation time towards the bottom of the conduction band. However, IVE evaluated using this technique is affected by the poor knowledge of the valence band dispersion at large k values. This problem is circumvented in the DT measurements, in which only conduction band states are involved. The DT decay time spectrum provided the IVE value of 0.97 ± 0.02 eV, close to the photoemission data. Comparison of DT and DR intervalley scattering onsets allowed estimating the hole mass as 1.4m0. Modelling of the DR transients with rate equations produced intra-and intervalley electron - LO phonon scattering times of 30 and 15 fs, respectively.

10104-20, Session 5

Nanoscale cathodoluminescence of a narrow band distributed Bragg reflector realized by GaN:Ge modulation doping

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Distributed Bragg reflectors (DBRs) have widespread use as optical mirrors and can be monolithically integrated into light-emitting semiconductor devices. The increased reflectivity of DBR structures results from constructive interference of light reflected at interfaces between layers with different refractive index. Usually, the periodic growth of two different materials is a convenient way of realizing DBR structures. Recently, DBR structures solely based on modulation doped GaN layers were developed showing 95 % reflectivity in the near UV [1]. Here, the refractive index change is obtained by periodic modulation of Ge doping concentration via the Burstein-Moss-effect. The expected refractive index contrast of the DBR layers is about 2 %.

Using cathodoluminescence spectroscopy performed in a scanning transmission electron microscope (STEM-CL), we analyze the optical and structural properties of a modulation doped GaN:Ge DBR with InGaN multiple quantum well on top. The structure was grown by metal organic vapor phase epitaxy on a sapphire substrate with a GaN buffer layer and consists of 100 pairs of GaN/GaN:Ge bilayers. The nominal doping concentration was set to 1.5 x 10^(20) cm^(-3) for the GaN:Ge.

Cross-sectional STEM-CL exhibits a modulation of panchromatic intensity in the DBR layers at 15 K. In the GaN:Ge DBR layer the excitonic emission at 356.8 nm is strongly enhanced compared to the undoped layer. On the high energy side a band-band recombination at 352 nm is apparent indicating an electron concentration exceeding the Mott transition in those GaN:Ge layers.

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10104-21, Session 5

Gallium nitride: a material for future betavoltaic

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Deep space exploration, use of sensors and devices at harsh climate conditions or in remote, hardly accessible areas, requires solutions, which will be modern and reliable on one hand and have a long lifetime on the other hand. One of the ideas, which meet these requirements is betavoltaic battery.

This concept is known since the 50s of the twentieth century and is based on the conversion of energy from radioactive elements using semiconductor p-n junctions. However, the rapid development of semiconductors of wide energy gap (mainly GaN), opened new possibilities of more efficient energy conversion. The idea of the betavoltaic battery is based on fabricating the semiconductor p-n junction, in a similar but not identical way to standard photovoltaic cells. The design of the structure has to be combined with the choice of the most appropriate source of beta particles.

Within the present work we demonstrate the modelling, design and the first tests of betavoltaic structure based on GaN p-n junction. The betavoltaic structures were fabricated by MOVPE on sapphire or gallium nitride substrate. The structures were tested by irradiating with electrons inside SEM. The signal detection was performed using EBIC (electron beam induced current) system. The use of electron beam in SEM, made possible to tune the acceleration voltage and the kinetic energy of electrons, allowing the simulation of irradiation using various radioactive sources. We also test various types of top metallization schemes to optimize the overall design of the device.

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10104-22, Session 6

Impact of InGaN alloy disorder on LED properties *(Invited Paper)*

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It emerges that LEDs properties are strongly impacted by intrinsic disorder induced by random In compositional fluctuations. They obviously impact the light emission spectrum and carrier mobilities. The quantitative evaluation of their impact in full heterostructures is made difficult by the extreme demand on computing resources when calculating solutions of the Schrödinger equation for a disordered 3D potential map. Calculations are then limited to small volumes and to the first few quantum states, not allowing for simulations of transport properties in full devices. It was recently shown in a simplified model that disorder can account for a turn-on voltage of LEDs smaller by 1V compared to standard simulations. We will present novel theoretical and modeling tools of disorder, namely the Filoche-Mayboroda 3D localization landscape theory, which from the original disordered energy map provides an effective potential which allows to use standard transport equations while accounting for microscopic disorder. We thus gain a deep understanding of various effects of disorder in nitride heterostructures on their electrical and optoelectronic properties. As a first application of the new tool we model our detailed measurements of the absorption edge of InGaN/GaN quantum wells with varying In composition. The tool is then applied to carrier transport in full LED structures. The effective potential increases current at a given bias voltage by accounting for two quantum effects of disorder, tunneling and confinement, which together smooth out potential discontinuities in the heterostructure. Quantum efficiency, Auger and leakage droop, ideality factor of the LED will be discussed.

10104-23, Session 6

Electrical and optical properties of flexible nanowire blue light-emitting diodes under mechanical bending

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III-Nitride-based nanowire LEDs have shown high internal quantum efficiency and stable light emission over a wide current range to enable white phosphor-free white-light emission. The structures provide a unique advantage for flexible electronics where the out-of-plane three-dimensional nanowires are invariant to applied bending. Testing this concept, InGaN dot-in-wire light-emitting diodes on sapphire substrates were transferred onto flexible polyethylene terephthalate (PET) substrates using a bonding and laser-liftoff process.

$In_{0.15}Ga_{0.85}N$ nanowire blue LEDs were grown on sapphire substrates having Ni/Au contacts applied to the top p-doped region and a lateral insulating polyimide layer applied between the nanowires. The nanowire structures were then bonded onto a transfer wafer and separated from its sapphire growth substrate by laser-liftoff (LLO) using a 266 nm KrF laser. A double-transfer technique, where the inverted LED structures were then transferred and bonded onto the PET with a silver-based adhesive that formed the final bottom contact. The LEDs before and after the transfer process did not show measurable degradation in the I-V and optical characteristics. The 425 nm luminescence peak was found to remain constant during applied mechanical strain on the flexible substrate suggesting the nanowire LEDs did not experience any plane-strain during bending. A constant 2.5 V turn-on voltage, and a forward current of 0.4 mA at 4 V was measured under concave and convex bending. Atomic force and scanning electron microscopy characterization will also be shown of the nanowire device before and after double transfer as well as numerical simulation of the mechanical motion of the nanowire structures during bending.

10104-24, Session 6

Radiative recombination in polar, nonpolar, and semipolar III-nitride quantum wells

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Efficient radiative recombination is one of the key properties enabling high performance light emitting devices. We have performed an in-depth experimental analysis of radiative recombination in polar, nonpolar, and semipolar III-nitride quantum wells (QWs), which allows us to elucidate its mechanisms. We are able to distinguish between localized and free exciton recombination, we can account for exciton dissociation, we clearly see the effect of polarization fields via the quantum-confined Stark effect, and we observe the effect of the valence band structure associated with crystal orientation and strain.

Experimentally, the radiative lifetimes are obtained from time-resolved photoluminescence measurements from 5 K to room temperature at various excitation power densities.

The temperature dependence of the radiative lifetime reveals localization of excitons at low temperatures, while at higher temperatures free excitons dominate. The localization energies range between about 4 meV for some c-plane samples to about 50 meV for some nonpolar QWs. Above about 200 K, free excitons become partly dissociated into free electrons and holes.

The room-temperature radiative lifetime shows a strong effect of polarization fields separating the electron and hole wavefunctions. For polar QWs the minimum is about 2 ns for QWs less than 1.5 nm thick. Semipolar or nonpolar QWs exhibit RT radiative lifetimes of 0.3 to 0.5 ns. This can be

partly attributed to a larger exciton binding energy. A major contribution also stems from a reduced hole effective mass in semi- or nonpolar QWs. This becomes particularly evident for strain-controlled nonpolar QWs grown on a metamorphic AlInN buffer.

10104-25, Session 6

Photo-induced droop in blue to red light-emitting GaInN-GaN heterostructures operating from 480 to 620 nm

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Despite an already existing abundant literature dedicated to report of lot of experimental investigations towards the understanting of the mechanisms that rule the limitation of intense light emission in nitride-based heterostructures, there are still some issues that are not fully elucidated. This is probably related to the lack of investigations away from the blue and aquamarine light regions. In this communication we cover the 480 nm to 620 nm range by using a series of samples with different designs: single and multiple GaInN-GaN quantum wells. This paper is limited to heterostructures grown along the polar orientation. By changing the well width, and the indium content we could tune in the one hand the Quantum Confined Stark Effect that is to say the intrinsic radiative recombination rate while we could tune the crystalline quality by using strain-compensated GaInN-GaN-AlGaN designs. Finally, by changing our optical pump density we modified the intrinsic non radiative Auger. Given an emission wavelength, we find that the photoexcitation density P for the onset of substantial Auger effect to increase with the number of wells. Using an ABC-type modelling we find a clear 3/2 power law correlation between parameters B and C. This behavior is discussed in terms of electron-hole coulomb interaction and electron-electron repulsion in photo-excited samples. In condition of efficient Auger recombination, the variation of the internal quantum efficiency with photoexcitation density is ruled by a universal power law independent of the design: IQE = IQE0 – a log10 P with a =16 %cm2/Watt.

10104-26, Session 6

Comparison of photoemission performance of AlGaN/GaN photocathodes with different GaN thickness

Junju Zhang, Nanjing Univ. of Science and Technology (China)

III-nitride photocathode has become an attractive candidate due to its wide band gap, stable physical and chemical properties and low dark current. Based on negative electron affinity (NEA) AlGaN photocathodes and micro-channel plate combination, a vacuum tube devices are utilized including ozone lager monitoring, UV astronomy, gas detection, water purification and medical appli-cations. AlGaN ultraviolet detection owns an advantage of the adjustable band gap. In the past few years, research on the uniform doping AlGaN photocathodes with the different Al com-ponents were carried on, but the spectral response performance of AlGaN photocathode with thin GaN surface (AlGaN/GaN) has not been discussed. On one side, the GaN photocathode has ideal surface electron escape probability and absorption coefficient, which could help the photoelectron escape from the photocathode surfacein reflective mode photocathode. On the other side, the cut-off wavelength of AlGaN photocathode can be tailored from 360 nm to 200 nm by increasing the Al content from 0 to 1 with optimal UV/solar rejection ratios. The AlGaN/GaN photocathode with GaN ultra-thin surface have high the surfaceelectron escape probability and change the UV/solar rejection ratiosof the AlGaN photocathode.

In this paper, we will investigate photoemission performance of three AlGaN/GaN photocathode with different GaN thickness. The AlGaN/GaN photocathodes are grown by metalorganic chemical vapor deposition (MOCVD). The GaN layer thickness of the AlGaN/GaN photocathodes is 7.5 nm, 2 nm and 0 nm. The reflectivity and transmittance has been tested, and their absorptivity has been obtained. In ultra-high vacuum system, the AlGaN/GaN photocathodes are activated, and the quantum efficiency (QE) curves are tested. The Cs/O activation results and quantum efficiency fitted results show that AlGaN/GaN photocathodes with a thick GaN layer can achieve higher photoemission and surface electron escape probability, and the quantum efficiency of them is 14.7%, 12.8% and 7.6% at 250 nm. But theUV/solar rejection ratio increases when the thickness of GaN decreases.

10104-27, Session 7

Room-temperature blue-emitting high-beta GaN nanobeam cavity lasers *(Invited Paper)*

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We report on the main features of blue emitting high-quality factor (Q) III-nitride nanobeam photonic crystal cavities containing a single InGaN/GaN quantum well (QW) gain medium. We show that the first generation of such nanobeams exhibits low-threshold (in the few microwatt range) continuous wave blue lasing (? ? 445-460 nm) at room temperature thanks to the combination of a high-Q value and a high spontaneous emission coupling factor (? > 0.7) ensuring efficient funneling of spontaneously emitted photons into the lasing mode. The transition from incoherent to coherent light emission is monitored through power-dependent second-order autocorrelation function measurements using a Hanbury-Brown and Twiss interferometer configuration, which show a progressive transition from thermal emission to the Poisson limit. Temperature-dependent input-output curves also reveal a complex interplay between the zero- and the two-dimensional nature of the QW gain medium. Subsequently, fabrication statistics performed on a second generation of blue nanobeam cavities show a twofold increase in the Q value (> 4000) with a high fabrication yield (> 95%) thanks to the use of a single-step pattern transfer process. Interestingly, such statistical analysis also indicates that disorder models comprised of normally-distributed hole size and position fluctuations could neither explain the dominant contribution to experimental quality factors nor the splitting between fundamental and first-order resonance wavelengths. Additionally, the introduction of a sidewall Bragg cross-grating coupler increased the integrated far-field intensity of those structures by nearly one order of magnitude.

10104-28, Session 7

Nanoscale characterization of GaN/InGaN multiple quantum well on GaN nanorods by photoluminescence spectroscopy

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New South Wales (Australia); Silke H. Christiansen, Max-Planck-Institut für die Physik des Lichts (Germany) and Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Gavin Conibeer, The Univ. of New South Wales (Australia)

GaN/InGaN multiple quantum wells (MQW) and GaN nanorods have been widely studied as a candidate material for high performance light emitting diodes. In this study, GaN/InGaN MQW on top of GaN nanorods are characterised in nanoscale using confocal microscopy associated with time-resolved photoluminescence. Nanorods are fabricated by etching planar GaN/InGaN MQWs on top of a GaN layer on a c-plane sapphire substrate. Photoluminescence efficiency from the GaN/InGaN nanorods is evidently higher than that from the planar structure, indicating the emission improvement. Using two-photon excitation spectroscopy, carrier transport and recombination mechanism in GaN/InGaN MQW and GaN nanorods are investigated. Excitation power dependent time-resolved photoluminescence (TRPL) prove that surface defects on GaN nanorod side walls have a strong influence on the luminescence property of the GaN/InGaN MWQs. Such surface defects can be eliminated by proper surface passivation. Moreover, densely packed nanorod array and sparsely standing nanorods have been studied for better understanding the individual property and collective effects from adjacent nanorods. Carrier diffusion and recombination model is developed to analyse carrier recombination process in GaN/InGaN MQW and GaN nanorods, which is consistent with the experimental results from two-photon excited and power dependent TRPL. The combination of the optical characterisation and theoretical analysis of carrier recombination provides novel insight into the carrier dynamics in GaN/InGaN nanorods and guidance for fabrication and optoelectronic device performance improvement.

10104-29, Session 7

Health-friendly high-quality white light using violet-green-red laser and InGaN nanowires-based true yellow nanowires light-emitting diodes

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White light based on blue laser – YAG:Ce3+ phosphor has the advantage of implementing solid-state lighting and optical wireless communications combined-functionalities in a single lamp. However, the blue light was found to disrupt melatonin production, and therefore the human circadian rhythm in general; while the yellow phosphor is susceptible to degradation by laser irradiation and also lack tunability in color rendering index (CRI). In this investigation, by using a violet laser, which has 50% less impact on circadian response, as compared to blue light, and an InGaN-quantum-disks nanowires-based light-emitting diode (NWs-LED), we address both issues simultaneously. The white light is therefore generated using violet-green-red lasers, in conjunction with a yellow NWs-LED realized using molecular beam epitaxy technique, on titanium-coated silicon substrates. Unlike the conventional quantum-well based LED, the NWs-LED showed efficiency-droop free behavior up to 29.5 A/cm2 with peak output power of 29 ?W. A low turn-on voltage of ~2.5 V was attributed to the formation of conducting titanium nitride layer at NWs nucleation site and improved fabrication process in the presence of relatively uniform height distribution. The 3D quantum confinement and the reduced band bending improve carriers-wavefunctions overlap, resulting in an IQE of ~39 %. By changing the relative intensities of the individual color components, CRI of > 85 was achieved with tunable correlated color temperature in the range of 2000 K to >7000 K, thus covering the desired room lighting conditions. Our architecture provides important considerations in designing smart solid-state lighting while addressing the harmful effect of blue light.

10104-30, Session 7

Localization in AlGaN nanowires probed by photon correlation spectroscopy

Matthias Belloeil, Bruno Daudin, Bruno Gayral, Commissariat à l'Énergie Atomique (France)

AlxGa1-xN nanowires (NWs) are considered to be a promising solution for solid-state ultraviolet (UV) emission. The basic physics of ternary alloys in NWs, and in particular of AlGaN NWs is however still to be explored.

Here we report on the study of the structural and optical properties of AlGaN sections grown on top of GaN NWs on Si (111) substrates by plasma-assisted molecular beam epitaxy, in particular as a function of AlGaN growth temperature and ternary alloy composition

Several series of samples with AlxGa1-xN sections on top of GaN NWs were grown in N-rich conditions, at different average AlN molar fractions (x in the 0.3-0.6 range) and various growth temperatures.

Microphotoluminescence of single nanowires reveals a broad spectrum made of sharp lines with linewidths in the 1-5 meV range. This is similar to what one obtains when probing in luminescence an ensemble of quantum dots. We thereafter performed photon correlation measurements in a Hanbury-Brown and Twiss set-up, which showed that indeed, antibunching is observed when probing a single line. Such a single AlGaN nanowire thus behaves as a collection of quantum dots, which we attribute to localization centers due to Ga-richer regions in the AlGaN matrix.

The mere counting of the number of sharp lines observed thus allows to determine the spatial density of such localized emission centers. We will also discuss time-resolved photoluminescence on such sharp emission lines, which allows to directly probe the size homogeneity of these localization centers in the AlGaN alloy.

10104-31, Session 7

InGaN quantum dots by quantum size controlled photoelectrochemical etching

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III-nitride quantum dots (QDs) have significant potential for single-photon sources or gain media for low threshold and high efficiency visible and UV lasers, among others. “Bottom-up” Stranski? Krastanov growth is widely used, however both the size distribution and densities are difficult to precisely control. Here, we show that a top-down fabrication process that itself can be controlled by the properties of the nanostructures being fabricated. This process, called quantum size controlled photoelectrochemical (QSC-PEC) etching, uses laser excitation at a selected and narrowband wavelength to control the final sizes of the QDs through an etch that self-terminates when the QD band gaps increase due to quantum confinement effects until they exceed the energy of the incident photons. Beginning with epitaxially grown InGaN films, we examine the etch process from large to quantum-scale nanostructures with AFM, TEM, and photoluminescence measurements. Quantitative analysis of size and density of the ensemble are made after image-post processing techniques and deconvolution of the AFM tip and QD. We further investigate the passivation of the QDs through regrowth of AlGaN and GaN capping layers, as well as fabrication of multilayers of QDs from multiple-quantum well structures. These results show the potential for a combination of unprecedented uniformity and density towards InGaN QD devices. Sandia National Laboratories is a multiprogram 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.

10104-32, Session 8

Phonon-assisted optical response in hexagonal boron nitride *(Invited Paper)*

Guillaume Cassabois, Univ. Montpellier (France)

Hexagonal boron nitride (hBN) is a wide bandgap semiconductor with a large range of basic applications relying on its low dielectric constant, high thermal conductivity, and chemical inertness. The growth of high-quality crystals in 2004 has revealed that hBN is also a promising material for light-emitting devices in the deep ultraviolet domain, as illustrated by the demonstration of lasing at 215 nm by accelerated electron excitation [1], and also the operation of field emitter display-type devices in the deep ultraviolet [2]. With a honeycomb structure similar to graphene, bulk hBN has recently gained tremendous attention as an exceptional substrate for graphene with an atomically smooth surface, and more generally, as a fundamental building block of Van der Waals heterostructures [3].

I will discuss our recent studies showing that the optical response in hBN displays prominent evidence for phonon-assisted optical transitions. First of all, by two-photon spectroscopy, we have demonstrated that the intrinsic optical properties at the band edge are characteristic of an indirect bandgap material [4]. I will further discuss our experimental evidence that transverse optical phonons at the K point of the Brillouin zone assist inter-K valley scattering in hexagonal boron nitride, thanks to the presence of a density of final electronic states coming from extended stacking faults [5]. Finally, I will present our measurements of the vibronic spectrum in a point defect in hBN, displaying a remarkable mapping with the phonon density of states, and in particular a suppression of the phonon-assisted recombination signal at the phonon gap energy [6].

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10104-33, Session 8

Single-photon emission from a high-purity hexagonal boron nitride crystal *(Invited Paper)*

Luis J. Martinez, Thomas Pelini, Ctr. National de la Recherche Scientifique (France); Victor Waselowski, Jeronimo R. Maze, Pontificia Univ. Católica de Chile (Chile); Bernard Gil, Guillaume Cassabois, Vincent Jacques, Ctr. National de la Recherche Scientifique (France)

Point-like defects in wide-bandgap materials are at the heart of a broad range of emerging applications including quantum information processing and metrology [1]. A well-known example is the nitrogen-vacancy (NV) defect in diamond, which can be used as a solid-state qubit to perform elaborate quantum information protocols [2] and highly sensitive magnetic field sensing [3]. These results motivate the search of new defects in other wide-bandgap materials, which would offer an expanded range of functionalities compared to NV defects in diamond.

In that context, hexagonal boron nitride (hBN) appears as an appealing material. First, it has a 6-eV bandgap, which is ideally suited to host optically active defects with energy levels deeply buried between the valence band and the conduction band. Second, hBN is an electrical insulator with a two-dimensional (2D) honeycomb structure, which is a key element of Van der Waals heterostructures. Such “artificial” materials are currently attracting a great interest owing to their unique mechanical, electrical and optical properties [4]. Combining these properties with individual quantum systems would likely open new perspectives in quantum technologies.

In this talk, I will report on the optical detection of individual defects hosted in a high-purity hBN crystal. Stable single photon emission is demonstrated under ambient conditions by means of photon correlation measurements [5]. A detailed analysis of the photophysical properties of the defect reveals a highly efficient radiative transition, leading to one of the brightest single photon source reported to date from a bulk, unpatterned, material. These results make a bridge between the physics of 2D materials and quantum technologies, and pave the way towards applications of van der Waals heterostructures in photonic-based quantum information science, metrology and optoelectronics.

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10104-34, Session 8

Exfoliated beta-Ga2O3 nanolayer for device applications *(Invited Paper)*

Jihyun Kim, Korea Univ. (Korea, Republic of)

Beta-Ga2O3 is a very intriguing material due to its large band-gap (4.9 eV), good chemical stability and availability of free-standing substrate. Recently, we demonstrated quasi-two-dimensional (2D) ?-Ga2O3 nano-belt by a mechanical exfoliation method, followed by fabrication into thin-film transistors and solar-blind photodetector. This mechanical exfoliation allowed us to produce ?-Ga2O3 nano-belts with a pristine surface on an arbitrary substrate. Firstly, ?-Ga2O3 nano-belt based transistor displayed a high on/off ratio up to 1E7 over the operating temperatures of 20 °C to 250 °C. The electrical characteristics were maintained after a month-long storage in an air ambient. Also, the solar-blind photodetectors based on beta-Ga2O3 nanolayer showed very high responsivity and excellent spectrum selectivity. Our work can motivate the applications of 2D ?-Ga2O3 into novel (opto) electronic devices for hostile environments. The details of the fabrication and characterization methods will be presented at the conference.

10104-35, Session 8

Demonstration of uniform and reliable GaN ultraviolet p-i-n avalanche photodiode arrays with large detection

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The epitaxial layers for 4?4 GaN ultraviolet (UV) p-i-n APD arrays with large detection area of 75?75 μm2 were grown by MOCVD. To obtain improved device performance, various growth and doping parameters were studied for growth on free-standing GaN substrates. For the fabrication of top-illuminated 4?4 UV-APD arrays, a low-damage inductively coupled plasma mesa etch, optimized n-type and p-type ohmic contacts, a PECVD-SiO2 passivation, accessing via holes using dry etching, and bonding pads for metal interconnects were employed. To verify the uniformity of the UV-APD array, the dark current and photocurrent of individual elements in the UV-APD array were measured. Neither microplasmas nor premature junction breakdown luminescence was visually observed for reverse-bias voltages up to near an avalanche breakdown. The average breakdown voltage of 16-element of the UV-APD array was 96 V with standard deviation of 0.6 V. In addition, the dark current density and photocurrent density of UV-APD array were below (6.5±1.8)?10-7 A/cm2 and (5.7±1.1)?10-6 A/cm2 for reverse bias voltages below 50 % of the average avalanche breakdown voltage of UV-APD array, respectively. Also, we confirmed the stability of 4?4 UV-APD array by performing the multiple reverse-bias I-V scans. With repeated tests, the measured 4-element in the 4?4 UV-APD array showed almost same dark current density and consistent breakdown voltages. These results show that low leakage current densities and breakdown voltages of each element are uniform and stable in the 4?4 UV-APD array. Detailed material growth, device fabrication techniques, and characterization of 4?4 UV-APD array will be presented.

10104-36, Session 8

Growth of tapered GaN nanorod and the study of its growth mechanism

Xu Zhang, Charng-Gan Tu, Yu-Feng Yao, Chen-Yao Chao, Sheng-Hung Chen, Chun-Han Lin, Chia-Ying Su, Yean-Woei Kiang, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

In a core-shell quantum-well (QW) nanorod (NR) structure, because of the non-uniform constituent atom supply for QW growth at different heights on a sidewall, the QW thickness and indium content vary with NR height. Multi-section NRs can be grown by controlling the supply duration of Ga source for decreasing the size of catalytic Ga droplet and hence tapering the NR cross-sectional size. The sidewall QWs of such a multi-section NR can emit light of a broad spectrum due to the larger variation ranges of QW thickness and indium content between sections of different cross-sectional sizes. In this paper, besides the growth processes of the aforementioned NR structures are reported, two models are built for simulating the sidewall QW growth and the tapering process of NR. Based on one of the models, the theories show the consistent results of increasing QW thickness and indium content in increasing NR height with the experimental observations. Based on another model, Ga adatoms diffuse on the slant facets from the Ga droplet on the NR top to deposit GaN on the slant facets for forming a gradient layer. In this situation, the angle of the slant facet increases from ~43 to ~62 degrees during the tapering process. The results are consistent with what observed in experiment. In this paper, besides NRs grown from patterned circular holes, the growth results of NRs from patterned elliptical holes are illustrated.

10104-37, Session 8

Electrically conductive ZnO/GaN distributed Bragg reflectors grown by hybrid plasma-assisted molecular beam epitaxy

Filip Hjort, Seyed Ehsan Hashemi, David Adolph, Tommy Ive, Åsa Haglund, Chalmers Univ. of Technology (Sweden)

III-nitride-based vertical-cavity surface-emitting lasers have so far used intracavity contacting schemes since electrically conductive distributed Bragg reflectors (DBRs) have been difficult to achieve. A promising material combination for conductive DBRs is ZnO/GaN due to the small conduction band offset and ease of n-type doping. In addition, this combination offers a small lattice mismatch and high refractive index contrast, which could yield a mirror with a broad stopband and a high peak reflectivity using less than 20 DBR-pairs.

A crack-free ZnO/GaN DBR was grown by hybrid PA-MBE, where both materials were grown in the same chamber. The ZnO layers were 31-36 nm thick and had an electron concentration of 1x10^19 cm^-3, while the GaN layers were 80-116 nm thick with an electron concentration of 2x10^18 cm^-3. The root-mean-square surface roughness was 2.1 nm. The ZnO layers were strained, which can reduce the vertical resistance. In order to measure the resistance, mesa structures were formed by dry etching through the top 3 DBR-pairs and depositing non-annealed Al-contacts on the GaN-layers at the top and next to the mesas. The measured specific series resistance was dominated by the lateral and contact contributions and gave an upper limit of 10^-3 ?cm^2 for the vertical resistance, corresponding to a resistance well below 100 ? for a 100 μm diameter mesa with 20 DBR-pairs. This is the first report on electrically conductive ZnO/GaN DBRs and the upper limit of the resistance reported here is comparable to the lowest values reported for III-nitride-based DBRs.

10104-38, Session 9

Thermal characterization for GaN electronics: Raman thermography and thermoreflectance *(Invited Paper)*

Martin Kuball, James W. Pomeroy, Univ. of Bristol (United Kingdom)

GaN electronics delivers unprecedented electrical power, and therefore its heat sinking is critically important. We report on the thermal characterization of GaN electronics using Raman thermography and thermoreflectance. The role of interlayers, substrate, die attach and device design on device thermal management will be discussed. (INVITED PRESENTATION FOR “Gallium Nitride Materials and Devices XII” (OE107).

10104-39, Session 9

Progress and future challenges of SiC power devices *(Invited Paper)*

Tsunenobu Kimoto, Kyoto Univ. (Japan)

Power semiconductor devices have attracted increasing attention as key components in a variety of power conversion systems. Although the performance of Si power devices has remarkably been improved, silicon carbide (SiC) (and gallium nitride (GaN)) is promising for advanced high-voltage, low-loss, and fast power devices, which can substantially outperform Si-based counterparts. Through recent progress in SiC growth and device technologies, production of 600 – 1700 V SiC Schottky barrier diodes and power MOSFETs has started, and remarkable improvement of energy efficiency has been demonstrated in real systems such as power supplies, air conditioners, photovoltaic power converters, and railcars. In this paper, recent progress of SiC power devices is reviewed. The major achievements include 1.2 kV – 0.0012 Ohmcm2 trench MOSFETs, 3 kV reverse-blocking MOSFETs, 27 kV PiN diodes, 23 kV bipolar junction transistors, and 16 kV – 60 A n-channel IGBTs. Several system applications will be also introduced.

In spite of the promising potential of SiC power devices, however, basic understanding of material science and device physics associated with SiC is still poor, leading to the lack of guidelines for defect control and thereby further improvement of device performance/reliability. In this paper, several important topics including the oxide/semiconductor interface, carrier lifetimes, and high-field phenomena in SiC are also reviewed.

10104-40, Session 9

Current status and future on GaN power devices for automobile applications *(Invited Paper)*

Tetsu Kachi, Nagoya University (Japan)

Over the past decade, the performance of GaN power devices has rapidly improved. There are two types of devices currently being developed, with either a lateral or a vertical structure. Though mainstream GaN power devices have still a lateral structure, vertical structure devices that is on GaN power devices have recently attracted additional research attention. The vertical structure has the advantages of a small chip size, easy wiring, a high breakdown voltage, and current-collapse-free operation. These characteristics are highly suited for high-power applications, for example, to control high-power motors used in electric automobiles.

Though recent reports showed high performance of the vertical structure, the development issues of the fabrication process still remain. The main issue is the quality of GaN substrates. Recent substrates have sufficient quality for high-voltage experiments like fabricating high-voltage devices, which make possible to obtain high-voltage devices over 1kV. However, the entire GaN substrate area does not yet have a uniform quality. It is the large issue. Other important issue is a normally-off gate structure and the gate insulator. Gate structure of the threshold voltage of > 3V like inverted type gate must be developed. The gate insulator which has low interface state density and high reliability is also required. Progress of the gate insulator is very rapid and low interface state density was established using SiO2 and resulted in the inverted MOSFET operation. The recent progress of the on GaN power devices will inspire the researches more.

10104-41, Session 9

Vertical GaN transistors for power electronics *(Invited Paper)*

Min Sun, Yuhao Zhang, Massachusetts Institute of Technology (United States); Ming Pan, Xiang Gao, IQE RF (United States); Tomas Palacios, Massachusetts Institute of Technology (United States)

A new generation of power electronics based on wide bandgap semiconductors is expected to significantly reduce the losses in power conversion circuits and, at the same time, change the form factor of power systems through a significant increase in the power density. Overall, energy savings greater than 10% of the world's energy consumption could be possible.

Vertical GaN power devices are very exciting candidates for future power electronics, however their development has been hindered by the high cost of bulk GaN and the relatively poor switching characteristics demonstrated so far by these devices. In this talk, we will describe our group's work on developing a new generation of vertical FET (VFET) devices that addresses the challenges of conventional power vertical GaN transistors. The proposed VFET structure does not require a p-doped GaN current-blocking layer or material regrowth, and a GaN VFET with 0.5 V threshold voltage and 1011 on/off current ratio was demonstrated. In addition, although the best performance is still found on devices grown on bulk GaN substrates, we will also demonstrate the feasibility of using vertical devices grown on a silicon substrate.

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10104-42, Session 9

Optimal GaN HEMTs: from materials and device design to compact model of the 2DEG charge density

Kexin Li, Shaloo Rakheja, NYU Tandon School of Engineering (United States)

Despite the significant progress in the field of GaN high electron-mobility transistors (HEMTs), issues pertaining to current collapse and Joule heating under high terminal voltages have limited the widespread deployment of GaN technology. This work explores the opportunities of alternate channel and barrier materials and novel heterostructures to improve the high-power and high frequency performance of GaN HEMTs. By solving the coupled Schrödinger-Poisson equation in the heterostructure and including the polarization-induced charges, we obtain the 2DEG carrier density in the channel for various thicknesses and material composition of the barrier and channel layers. Optimal material and device parameters that maximize performance metrics of the device – 3dB gain, maximum cut-off frequency, and maximum oscillation frequency – are identified. Specifically, we examine the barrier materials such as AlxGa1-xN, AlxIn1-xN, and channel materials: InxGa1-xN and InN. We also present a new, physically motivated and experimentally verified compact model for the 2DEG charges in GaN heterostructure. The charge model is geometry scalable, aware of material composition, and includes the dynamic trapping and self-heating phenomena. The dynamic phenomena are represented as equivalent RC lumped elements in the Verilog-A implementation of the model. The model is also verified against results from the commercial TCAD simulator Sentaurus from Synopsys. The material- and device-centric analyses in this work allow us to study the limits and opportunities of GaN technology. Additionally, the compact charge model can be easily integrated in a hierarchical circuit simulator, such as Keysight ADS and CADENCE, to facilitate circuit design and optimization of various technology parameters.

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10104-43, Session 10

GaN HEMTs with p-GaN gate: field- and time-dependent degradation *(Invited Paper)*

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GaN-based high electron mobility transistors have recently emerged as a promising alternative to their silicon counterpart for application in power electronics. The high breakdown voltage of GaN enables kV-range application, while the high mobility of the channel and the low gate capacitance permit to significantly reduce the switching losses. 30 A devices with on-resistance smaller than 50 mOhm have been demonstrated, thus clearing the way for a massive market penetration. A promising approach to obtain normally-off operation is to use a p-GaN gate: the acceptors in the p-GaN gate lift the band diagram of the structure, thus depleting the 2DEG with zero gate voltage. In normally-off transistors, the gate is subject to a high positive bias (>6 V): for this reason, it is important to study and evaluate the stability of the gate stack.

This paper reviews our most recent results on the failure of normally-off GaN-based transistors with p-GaN gate. Based on combined step-stress experiments, constant voltage stress tests, electroluminescence analysis and 2D simulations we show that: (i) exposure to high gate voltages may lead to the permanent failure of the devices, due to the creation to a shunt path between the gate metal and the 2DEG; (ii) time-to-failure (TTF) is Weibull-distributed, and has an exponential dependence on stress voltage; (iii) the shunt paths created after stress can be identified by EL measurements; (iv) device degradation is due to a defect generation/percolation process that takes place in the p-GaN layer, due to the high electric field reached during stress.

10104-44, Session 10

Identify defects in AlGaN/GaN high-electron mobility transistors with sub-bandgap optical pumping *(Invited Paper)*

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AlGaN/GaN high electron mobility transistors (HEMTs) showed its promising performance in high power and high frequency, which can be used for applications such as satellite-based communication networks, inverter units in hybrid electric vehicles and advanced radar systems. However, intrinsic defects and defects generated during the device fabrication degraded HEMT performance, such as drain current collapse, high gate leakage, and lower rf power density and power add efficiency. Furthermore, subsequent electrical stressing of the HEMTs during operation leads to creation of more traps and further device degradation through various mechanisms, including gate contact sinking, shallow trap formations, and the inverse piezoelectric effect. It is highly desirable to have non-destructive methods available to identify the activation energies of the defects and spatial location of trap states in HEMT. A sub-bandgap optical pumping technique was developed to identify trap locations in AlGaN/GaN HEMTs. By varying photon fluxes, the traps with different activation energies appeared at different photon flux levels. This implies that the defects originate at different physical locations in the HEMT. The locations of the traps identified with the sub-bandgap optical pumping methods confirmed by gate pulse measurements under optical pumping.

10104-45, Session 10

Electrical characteristics of high-power AlGaN-GaN high-electron mobility transistors irradiated with protons and heavy ions

Yongkun Sin, Jeremy Bonsall, Zachary Lingley, Miles Brodie, Brendan Foran, Maribeth Mason, The Aerospace Corp. (United States)

Leading GaN HEMT manufacturers have recently reported excellent RF power characteristics and encouraging reliability, but long-term reliability in the space environment still remains a major concern due to a large number of defects and traps present in the bulk as well as at the surface. Furthermore, degradation mechanisms in GaN HEMTs are still not well understood. Thus, reliability and radiation effects of GaN HEMTs should be studied before solid state power amplifiers (SSPAs) based on GaN HEMT technology are successfully deployed in space satellite systems. For the present study, we investigated electrical characteristics of high-power GaN HEMTs irradiated with protons and heavy ions followed by analyses using micro-analytical techniques.

We studied high-power GaN HEMTs grown on SiC substrates. Our HEMT devices had a Ni (Pt)-Au Schottky gate length of 0.4 um, a total gate width of 10 ? 350 um periphery, and a field plate. Twelve devices were irradiated with protons and heavy ions under various bias conditions. We compared electrical characteristics of the GaN HEMTs including threshold voltage, transconductance, and drain current before and after they were irradiated. Then, current-mode deep level transient spectroscopy (I-DLTS) and capacitance-mode DLTS were employed to study pre- and post-irradiation trap characteristics in the GaN HEMTs. Lastly, focused ion beam was employed to prepare TEM specimen for defect analysis using a high resolution TEM. Our detailed analysis results will be presented along with our understanding on the role that defects and traps play in the degradation of electrical characteristics of irradiated GaN HEMTs.

10104-46, Session 11

200-mm GaN/Si technology for power device applications *(Invited Paper)*

Takashi Egawa, Nagoya Institute of Technology (Japan)

An AlGaN/GaN HEMT on Si has received significant attention due to the availability of large sized Si substrate at low cost. The limiting factors for high quality GaN/Si are large lattice and thermal expansion-coefficient mismatches between GaN and Si, which lead to high dislocation densities, wafer bowing and crack formation. Therefore, it is imperative to grow high quality GaN/Si with minimum wafer bowing and without crack in order to improve the device performances.

The AlGaN/GaN HEMTs were grown on 8-inch Si substrates using MOCVD technique. The HEMT structure consisted of the high-temperature-grown AlN nucleation layer (HT-AlN NL), the HT-Al0.3Ga0.7N intermediate layer (HT-AlGaN IL), the AlGaN/AlN strained layer superlattice (SLS), the GaN layer and the Al0.26Ga0.74N barrier layer. The HT-AlN NL was effective in avoiding the reaction between Ga and Si, which resulted in the specular surface morphology. The characteristic of the HT-AlN NL affected the vertical breakdown characteristics. The wafer b owing can be minimized by use of SLS and GaN because of counter-balance of thermal and lattice mismatches between SLS and GaN.

The AlGaN/GaN HEMT exhibited a Hall mobility of 1730 cm2/vs, a sheet carrier density of 7.4x1012 cm-2 and the wafer bowing value of 42 um. The vertical voltage at 1 uA/mm was between 950 V and 1000 V across the wafer. The normally-off devices were fabricated by using gate-recess and MOS technology. The devices exhibited good dc characteristics with drain current maximum of 300 mA/mm, threshold voltage of +2.4 V and 3-terminal off-breakdown voltage of 1650 V.

10104-47, Session 11

Power electronic devices based on Al-rich AlGaN alloys *(Invited Paper)*

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As the performance of GaN- and SiC-based power devices becomes limited by fundamental material properties, semiconductors with larger bandgaps are appealing due to their superior material properties. For vertical devices, the Figure-of-Merit (FOM) comparing breakdown voltage and specific on-resistance scales as the bandgap to the 7.5 power and scales as bandgap to the 5 power for lateral devices. This talk will illustrate the potential for AlGaN alloys as a viable material for next-generation power devices.

We report on the growth and doping of Al0.3Ga0.7N epilayers used to fabricate quasi-vertical PN diodes with breakdown voltages in excess of 1600 volts. An effective critical electric field of 5.9 MV/cm was determined from the reverse current-voltage characteristics. We note that a Baliga FOM (Vbr2/ Rspec,on) of 150 MW/cm2 found in this study is the highest reported for an AlGaN PN diode.

The formation of 2D electron gases in both Al0.85Ga0.15N/Al0.7Ga0.3N and AlN/Al0.85Ga0.15N heterostructures was studied. By adjusting the thickness of and Si concentration in the barrier layer, the pinch-off voltage can be controlled from ~0 V to -15 V and the sheet resistance lowered to 1600 ohms/sqr. A high electron mobility transistor based on an AlN/Al0.85Ga0.15N heterostructure showed transistor operation, but poor contacts limited drain current. Low gate leakage characteristics enabled a Ion/Ioff current ratio greater than 10^7. A breakdown voltage of 810 V was achieved without a field plate for a gate-drain spacing of 10 um.

These device demonstrations serve to motivate further investigation of AlGaN alloys for high-voltage and power devices.

10104-48, Session 11

Piezoelectric modulation of surface voltage in GaN and AlGaN/GaN: charge screening effects and 2DEG

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Surface voltage response to pulses of piezoelectric polarization is measured with a Kelvin-probe providing a unique means for investigation of the dynamics of polarization induced sheet charge and 2DEG. Combined with biasing of the surface with a corona-deposited charge from accumulation to deep depletion and corresponding non-contact C-V type characterization, the technique identifies surface band bending and interface traps as key factors that affect the magnitude and time decay of piezoelectric polarization. For 2DEG structures, surface potential pinning is observed when the 2DEG is fully populated. Pinning is released by negative corona charging to fully deplete the 2DEG. These results are consistent with the role of surface states. Presently demonstrated polarization modulation and wafer scale measurements shall impact the in depth characterization and fundamental understanding of AlGaN/GaN 2DEG structures.

10104-49, Session 11

Investigation of GaN Fin-HEMTs with Micron-scale Fin Width

Li-Cheng Chang, Ming Yang, National Taiwan Univ. (Taiwan); Yi-Hong Jiang, National Taiwan University (Taiwan); Chao-Hsin Wu, National Taiwan Univ. (Taiwan)

AlGaN/GaN-based materials are widely investigated for the applications of power electronics due to their superior properties such as high breakdown voltage, low ON-resistance, and high thermal stability. For higher power efficiency and higher output power density, E-mode operation is critical for the development and the approaches have been proposed including recessed gate, fluorine treatment, and p-GaN layer insertion.

In this paper, we utilize the fin-shaped channel which can be considered as "Fin-HEMT" to adjust the threshold voltage (Vth) toward positive value. The gate metal here is deposited directly on the AlGaN/GaN semiconductor to form the Schottky contact. Although the fin-widths are all in the micron-scale, the shifts of Vth are still observable and with the smaller fin width, the Vth becomes more. This is attributed to the assistant of the side-gate control. The depletion layer formed by Schottky contact at side-gate will also deplete the 2DEG in the channel. Therefore, with the smaller fin width, the channel shows faster pinch off with increasing the gate bias which is similar to the double gate MESFET.

On the other hand, unlike to carrier transportation of the conventional FinFET with nano-scale fin width which is dominated by the surface scattering, our Fin-HEMTs with micron scale exhibits higher drain current than planar device and this is because of the smaller thermal resistance for the fin-HEMT. We extract the thermal resistance by varying the measured temperature and the thermal resistance of 2-?m-fin-HEMT and planar device is 58.5 K/W and 249.5 K/W, respectively.

10104-50, Session 12

GaN-based vertical-cavity surface-emitting lasers with AlInN/GaN distributed Bragg reflectors *(Invited Paper)*

Tetsuya Takeuchi, Satoshi Kamiyama, Motoaki Iwaya, Meijo Univ. (Japan); Isamu Akasaki, Meijo Univ. (Japan) and Nagoya Univ. (Japan)

GaN-based vertical cavity surface emitting lasers (VCSELs) are expected to be utilized in retinal scanning displays, adaptive headlights, and high-speed visible light communication systems. Recently, lasing operations of the VCSELs with a combination of two dielectric distributed Bragg reflectors (DBRs) or a combination of a top dielectric DBR and a bottom GaN-based DBR have been demonstrated. We have developed lattice-matched AlInN/GaN DBRs as GaN-based DBRs, having potentially high reflectivity. An negative aspect of the AlInN was requiring very low growth rate (less than 0.2 μm/h) to obtain high-quality AlInN layers, but we have optimized growth conditions of the AlInN with a growth rate over 0.5 μm/h. A peak reflectivity of a 40-pair AlInN/GaN DBR grown under such an optimized condition was reached to 99.6 %. We then fabricated a VCSEL structure on a GaN substrate, consisting of the 40-pair AlInN/GaN bottom DBR, a 4?-cavity containing an n-GaN/GaInN QW active region/p-AlGaN/p-GaN structure, an ITO current confinement electrode, and finally an 8-pair Nb2O5/SiO2 top DBR. Double intra-cavity contacts with an 8 μm aperture were fabricated. A maximum light output power of 3 mW and a threshold current of 7.3 mA were obtained in the VCSEL emitting 415 nm under continuous wave (CW) operation at room temperature (RT). An external differential quantum efficiency was estimated to be 13 %. In addition, we developed n-type conducting AlInN/GaN DBRs by using a concept of "polarization dilution" with modulation-doping of Si. A RT-CW operation of the VCSEL with the vertical current injection through such a conducting bottom DBR was achieved.

10104-51, Session 12

Recent Improvement in Nitride Lasers *(Invited Paper)*

Shingo Masui, Yoshitaka Nakatsu, Daiji Kasahara, Shin-ichi Nagahama, Nichia Corp. (Japan)

Since the first demonstration of violet InGaN-based laser diodes (LDs) in 1995, we have been researching to improve the output power and expand the lasing wavelength. Recently, visible LDs have much attention for the light source applying it into full color laser displays which have extremely large color reproduction characteristics. LDs light source have several advantage for laser display to compare with conventional mercury lamp, they are low consumption power, long life time, low cost, moment-lighting, safe to environments, and so on. Now some kinds of laser display products

with visible LDs light source have been increasing, for example large laser projector, 6 primary cinema laser projector, full color laser TV, laser pico-projector and so on.

In this presentation, we report our recent improvement of watt class blue and green GaN based LDs for laser display. These LDs were grown on c-face GaN substrates by metal organic chemical deposition. The laser chip was mounted on the heat sink by the junction down method in TO-ø9 mm package for the suppression of the thermal resistance. The optical output powers of 455nm blue LDs is obtained above 4.7 W at injection current of 3A. The average lifetime was estimated to be over 30,000 hours at case temperature of 65 degree C under 3A. In green LDs, 1 watt class 532 nm green LDs as same wavelength as second harmonic generation (SHG) green laser was developed and the wall plug efficiency was 12.1 %. And the longer lasing wavelength was achieved to 537 nm.

10104-52, Session 12

Demonstration of nitride-based lasers excited by electron beam *(Invited Paper)*

Motoaki Iwaya, Takafumi Hayashi, Noriaki Nagata, Takashi Senga, Sho Iwayama, Tetsuya Takeuchi, Satoshi Kamiyama, Meijo Univ. (Japan); Isamu Akasaki, Meijo Univ. (Japan) and Nagoya Univ. (Japan); Takahiro Matsumoto, Nagoya City Univ. (Japan)

The UV semiconductor-based laser sources are important for a variety of fields, including medical, mechanical processing, chemical processing, biology, and photonics. However, the development of UV-B and UV-C laser diodes is strongly hampered because of the difficulties with current injection technology such as the realization of both a high hole concentration and low resistivity p-type AlGaN with a high AlN molar fraction. Because laser oscillation from AlGaN, with a high AlN molar fraction, can be obtained under optical pumping, UV lasers with controllable wavelengths should be realized if this problem can be solved.

One promising technique for avoiding these problems is the use of electron beam excitation. Till date, nitride semiconductor-based lasers have been designed to achieve population inversion of the carrier and to oscillate due to current injection. However, as previously discussed, it is difficult to achieve wavelengths in UV-B and UV-C using this method. The conductivity control of nitride semiconductors is unnecessary using electron beam excitation. Therefore, it would be possible to expand the wavelength region for the laser action of nitride semiconductor-based lasers from deep UV to infrared if a nitride semiconductor-based laser could be oscillated via electron beam excitation. In this study, nitride-based lasers excited by electron beam were investigated, and laser emission was observed for the first time from a GaInN/GaN and GaN/AlGaN-based MQWs excited by an electron beam.

10104-53, Session 12

Modeling of optical and electrical confinements in nitride VCSELs

Patrycja Spiewak, Michal Wasiak, Robert P. Sarzala, Lodz Univ. of Technology (Poland)

Semiconductor nitride VCSELs (Vertical-Cavity Surface-Emitting Lasers) are devices with an enormous application potential. However, operation characteristics of the existing structures are far from expected for applications. One of the basic problems in these structures is how to make the current flow through the center of the active region. Therefore most of the existing nitride VCSELs have a semitransparent ITO (Indium Tin Oxide) contact [1], which has a high electrical conductivity. Also hybrid confinement constructions, with an ITO layer and an AlN-burried aperture were considered [2]. Although ITO has a high electrical conductivity it also has high absorption coefficient, hence other solutions to current confinement are investigated.

In this paper, we present numerical simulation of various types of existing nitride VCSELs, including structure with ITO layer and AlN-burried aperture. We analyzed threshold parameters, including threshold current, temperature distribution and order of the transverse mode induced in the laser. The results show that in the analyzed structures with AlN apertures of appropriate thickness, placed at the node of the standing wave, we observe a strong discrimination of non-fundamental modes. We also determined the values of electrical conductivity and absorption coefficient of the ITO layer for which the analyzed structures can lase.

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10104-54, Session 12

Lateral grating DFB AlGaInN laser diodes for optical communications and atomic clocks

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The AlGaInN material system allows for single transverse mode, ridge waveguide laser diodes to be fabricated with optical powers up to 100mW over a very wide range of wavelengths from u.v., ~380nm, to the visible, ~530nm, by tuning the indium content of the laser GaInN quantum well. AlGaInN blue-green laser diode technology, allowing the possibility of visible light communications that operate at very fast data rates (GHz) [1] and for next generation atomic optical clocks based on Sr (meeting the 88Sr+ cooling transition [5s2S1/2 -5p2P1/2] by using 422nm & 461nm) and a blue cooling transition for Rubidium (Rb) [4p65s2S1/2 - 4p66p2P3/2] at 420.2nm).Very narrow linewidths (<1MHz) are required for such applications, however in the present Fabry-Perot GaN LD's a broad mode comb is observed in spectral output. Ideally, a GaN DFB laser with an integrated etched grating to select and stabalise the longitudinal mode would be considered, however there are significant technical challenges to overcome before a 'conventional' buried DFB GaN laser can be realised. Lateral gratings on AlGaInN ridge waveguide laser diodes are reported in [2] as an alternative to 'conventional' buried DFB's and are more straightforward to fabricate while still achieving a good SMSR under pulsed operation. We report on efforts to improve lateral grating DFB performance to achieve even higher SMSRs and CW operation.

10104-55, Session 12

AlGaInN laser-diode technology for optical clocks and atom interferometry

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Optical clocks have demonstrated an improvement in temporal accuracy of several orders of magnitude over existing time standards based on caesium. Such systems hold great promise in many industrial sectors including financial time stamping, GPS-free navigation and network synchronisation. Atom interferometry has proven to be a reliable method of precision gravity sensing and finds application in geological studies, including earthquake warning systems and oil exploration. Such systems require a number of sophisticated lasers in a compact and reliable format for use outside of a laboratory environment, suitable for commercialisation and user transportation.

The AlGaInN material system allows for single transverse mode laser diodes to be fabricated with optical powers up to 100 mW and over a very wide range of wavelengths from U.V., ~380 nm, to the visible, ~530 nm. By tuning the indium content and thickness of the GaInN quantum well it is possible to directly target a wavelength of interest. Direct light generation at the required wavelength is crucial to reduce complexity of the overall system, to ensure compact systems suitable for transportations and to ensure a high wall-plug efficiency that is critical for space and mobile applications.

Hence, there is considerable interest in using AlGaInN laser technology for the next generation optical clocks and atom interferometry systems. This includes the [5s2S1/2-5p2P1/2] cooling transition in strontium+ ion optical clocks at 422 nm, the [5s21S0-5p1P1] cooling transition in neutral strontium clocks at 461 nm and the [5s2s1/2 – 6p2P3/2] transition in rubidium at 420 nm. These transitions are a few among an extensive list required. In addition to the requirements outlined above, narrow linewidths (<5 MHz) are required for the identified transitions and few kHz levels for other transitions. To meet these requirements we are pursuing both extended cavity laser (ECDL) geometries in the short term and distributed feedback architectures in the long term.

We have developed a range of AlGaInN diode-lasers targeted to meet the wavelength and power requirements suitable for optical clocks and atom interferometry systems. A packaging system has been developed optimised for ECDL narrow-linewidth operation and includes anti-reflection coatings on the facets optimised for the design. Multiple ECDL designs have been developed including gratings in Littrow configuration and filter-based rugged geometry designs optimal for narrow-linewidth operation. At the conference we will present details of the design of the structures and current performance related characteristics.

10104-73, Session 12

Suppressing the incorporation of carbon impurity in AlGaN:Mg for green LDs with low operation voltage

Jianping Liu, Suzhou Institute of Nano-Tech and Nano-Bionics (China)

This paper reports the influence of carbon impurities on electrical properties of AlGaN: Mg layer which is used in InGaN-based blue/green laser diodes (LDs) as the cladding layer. AlGaN layer grown by MOCVD usually contains more carbon impurity than GaN, especially when AlGaN is grown at a low temperature to avoid the degradation of InGaN/GaN quantum wells in green LD with high indium content. However, no experimental study on the effect of carbon impurity on the electrical properties of the AlGaN:Mg layer has been reported.

All AlGaN:Mg samples were grown on c-plane GaN/sapphire template at various growth pressure, growth rate and V/III ratio to suppress the carbon impurity concentration. These sample were then activated at 950? for 90s in nitrogen ambient. The hole concentration and resistivity of Al0.07Ga0.93N:Mg samples depend on carbon concentration. By reducing carbon concentration from 2?1018 to 5?1016 cm-3, the hole concentration increase from 7.5?1016 to 3.5?1017 cm-3, and thus the resistivity of p-Al0.07Ga0.93N decreases from 7.4 to 2.2 ?·cm .

Based on the analysis of the charge neutrality equation, we believe that the compensation effect of CGa(Al) as a shallow donor in AlGaN:Mg explains the dependence of the hole concentration and the resisitivity on the carbon concentration in our samples, which will be discussed in detail in this report.

By applying the optimized AlGaN:Mg grown at low temperature as the cladding layer, we have obtained green LD structures without thermal degradation in the InGaN active region. The differential resistance is 2.4 ? leading to V= 4.9 V at 4 kA/cm2. It lases at 508nm with Jth= 1.8 kA/cm2, and has a output power of 58 mW at a current density of 6 kA/cm2.

10104-56, Session 13

Current status and future works of high-power deep UV LEDs *(Invited Paper)*

Rakjun Choi, LG Innotek (Korea, Republic of)

Deep ultraviolet light emitting diodes (UV-C LEDs) are taking significant interest in varying applications such as disinfection and purification for air, water, and surface. Therefore, many reports have been published regarding the development and applications of UV-C LEDs, which have been adopted a home appliances recently. However, UV-C LEDs still have a number of challenges such as output power, cost, reliability, and manufacturability. In this talk, recent advances in epitaxial quality, device design, and reliability for high current driven UV-C LEDs will be presented.

10104-57, Session 13

Electron beam pumping for high-power deep-UV emitters *(Invited Paper)*

Thomas Wunderer, PARC, A Xerox Co. (United States)

High-power optical sources that emit in the UV spectral range have applications that include bio-chem identification, decontamination, medical diagnostic and treatment, communications, and materials curing. Attempts to realize semiconductor UV sources by the conventional approach with a current-injection p-/n-junction diode have encountered numerous difficulties. This presentation will discuss the challenges, illustrate the current status of materials/device development, and describe the necessary building blocks, which include highly conductive p-type cladding layers, sophisticated electron-blocking layers, and high performance active zones. High current densities of more than 20kA/cm2 of a full LD heterostructure have been achieved. Optically pumped lasers have been demonstrated with low pump threshold down to a wavelength of 237nm. However, issues related to effective carrier injection and low absorption losses remain challenging when using high band gap p-type materials. Thus, a laser configuration that omits the use of p-doped materials is an attractive alternative.

We will present recent results towards realizing deep-UV lasers in the AlGaN materials system using electron beam excitation as the laser pumping strategy. A custom-built e-beam-pumping system has been developed that enables excitation of AlGaN gain chips with high-energy electrons (10-30keV) and high-power densities exceeding 1MW/cm2. AlGaN gain chip heterostructures for vertical laser emission will be described. Toward development of a compact deep-UV laser source, we report record high pulsed peak optical output power of more than 200mW of spontaneous emission at ?=246nm.

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10104-58, Session 13

Over 10% EQE AlGaN deep-UV LED developed by using transparent p-AlGaN contact layer *(Invited Paper)*

Hideki Hirayama, RIKEN (Japan); Takayoshi Takano, Panasonic Corp. (Japan); Jun Sakai, Panasonic Industrial Devices SUNX Co., Ltd. (Japan); Takuya Mino, Panasonic Corp. (Japan); Kenji Tsubaki, Panasonic Industrial Devices SUNX Co., Ltd. (Japan); Noritoshi Maeda, Masafumi Jo, RIKEN (Japan); Issei Ohshima, Takuma Matsumoto, Norihiko Kamata, Saitama Univ. (Japan)

AlGaN deep ultraviolet light-emitting diodes (DUV-LEDs) are attracting much attention for a wide variety of applications, however, the efficiency of DUV-LED is still low suppressed by low light-extraction efficiency (LEE). Transparent contact layer is considered to be necessary in order to obtain high LEE in AlGaN DUV LEDs. In this work, we demonstrate over 10% external quantum efficiency (EQE) in an AlGaN DUV-LED by using transparent p-AlGaN contact layer and highly reflective p-type electrode.

We fabricated AlGaN quantum well (QW) DUV LEDs with transparent p-AlGaN contact layers on AlN/sapphire templates. EQEs were compared between LEDs with Ni/Al highly reflective electrode and with conventional Ni/Au electrode. The transparency of the p-AlGaN contact layer was confirmed to be more than 97 %. The maximum EQE for 261 nm LEDs with Ni/Al and Ni/Au electrodes were approximately 2 and 3.3%, respectively. We confirmed that the LEE was increased by about 1.7 times. We also fabricated flip-chip (FC) UVC LED module with transparent p-AlGaN contact layer and reflective electrode. The FC LED module was encapsulated to increase LEE. The emission wavelengths were 276 nm. The EQE value under the forward current of 120 mA was increased from 2.7 to 8.6% by increasing an LEE. The output power of approximately 60 mW was obtained under the forward current of 150 mA. The EQE value was maximally increased up to 10.8%. LEE was estimated to be increased from 8.6 % to 25.5 % by introducing LEE enhancement structure.

10104-59, Session 13

Full-color and ultraviolet nanowire light-emitting diodes by selective area epitaxy *(Invited Paper)*

Zetian Mi, Univ. of Michigan (United States) and McGill Univ. (Canada); Yong-Ho Ra, Renjie Wang, Songrui Zhao, Binh Le, Xianhe Liu, McGill Univ. (Canada)

The monolithic integration of red, green and blue GaN-based LEDs directly on a single chip is critically important for smart lighting and full color display applications. We report on the first demonstration of full-color, single nanowire LEDs monolithically integrated on the same chip, which is achieved by incorporating multiple InGaN/GaN quantum dots in GaN nanowires with various diameters grown in one-step selective area epitaxy. Through detailed STEM studies, it is observed that the position, size, and composition of InGaN quantum dots depend critically on the nanowire diameter. For small diameter nanowires, quantum dots with high In content are positioned at the center of nanowires and are vertically aligned along the c-axis. With increasing nanowire diameter, however, the formation of quantum dots with reduced In content becomes more dominant on the semipolar planes. By exploiting such unique diameter-dependent quantum dot formation, we have shown that tunable emission across nearly the entire visible spectral range can be realized from single InGaN/GaN dot-in-nanowire structures grown on the same substrate in a single epitaxy step. Multicolor InGaN/GaN nanowire LEDs are also fabricated on the same chip, which exhibit excellent current?voltage characteristics and strong emission in the blue, green, orange, and red spectral ranges. We have further shown that nearly dislocation-free semipolar AlGaN templates can be achieved on c-plane sapphire through controlled nanowire coalescence by selective-area epitaxy. The semipolar AlGaN ultraviolet light-emitting diodes demonstrate excellent optical and electrical performance, including an internal quantum efficiency of 83% at room-temperature and a device turn-on voltage of 3.3V.

10104-60, Session 13

Dominant transverse-electric polarized emission from 298-nm MBE-grown AlN-delta-GaN quantum-well ultraviolet light-emitting diodes

Cheng Liu, Yu Kee Ooi, Rochester Institute of Technology (United States); S. M. Moududul Islam, Huili Grace Xing, Debdeep Jena, Cornell Univ. (United States); Jing Zhang, Rochester Institute of Technology (United States)

III-nitride based ultraviolet (UV) light emitting diodes (LEDs) are of considerable interest in replacing gas lasers and mercury lamps for numerous applications. Specifically, AlGaN quantum well (QW) based LEDs have been developed extensively but the external quantum efficiencies of which remain less than 10% for wavelengths <300 nm due to the high dislocation density, difficult p-type doping and most importantly, the physics and band structure from the three degeneration valence subbands. One solution to address this issue at deep UV wavelengths is by the use of the AlGaN-delta-GaN QW where the insertion of the delta-GaN layer can ensure the dominant conduction band (C) - heavy-hole (HH) transition, leading to large transverse-electric (TE) optical output.

Here, we proposed and investigated the physics and polarization-dependent optical characterizations of AlN-delta-GaN QW UV LED at ~300 nm. The LED structure is grown by Molecular Beam Epitaxy (MBE) where the delta-GaN layer is ~3-4 monolayer (QW-like) sandwiched by 2.5-nm AlN sub-QW layers. The physics analysis shows that the use of AlN-delta-GaN QW ensures a larger separation between the top HH subband and lower-energy bands, and strongly localizes the electron and HH wave functions toward the QW center and hence resulting in ~30-time enhancement in TE-polarized spontaneous emission rate, compared to that of a conventional $Al_{0.35}Ga_{0.65}N$ QW. The polarization-dependent electroluminescence measurements confirm our theoretical analysis; only TE-emission is detected while the transverse-magnetic (TM) emission is below noise level of the measurement apparatus, indicating the feasibility of high-efficiency TE-polarized UV emitters based on our proposed QW structure.

10104-61, Session 13

Improved light extraction and quantum efficiencies for UVB LEDs with UV-transparent p-AlGaN superlattices

Martin Guttmann, Martin Hermann, Johannes Enslin, Sarina Graupeter, Luca Sulmoni, Christian Kuhn, Tim Wernicke, Technische Univ. Berlin (Germany); Michael Kneissl, Technische Univ. Berlin (Germany) and Ferdinand-Braun-Institut (Germany)

Light emitting diodes (LEDs) in the UVB (280 nm – 315 nm) spectral range are of particular interest for applications such as plant growth lighting or phototherapy. In fact, LEDs offer numerous advantages compared to conventional ultraviolet light sources such as a tunable emission wavelength, a small form factor, and a minimal environmental impact. State-of-the-art devices utilize p-GaN and low aluminum mole fraction p-AlGaN layers to enable good ohmic contacts and low series resistances. However, these layers are also not transparent to UVB light thus limiting the light extraction efficiency (LEE). The exploitation of UV-transparent p-AlGaN layers together with high reflective metal contacts may significantly increase the LEE. In this paper, the output power of LEDs emitting at 310 nm with a UV-transparent

and absorbing Mg-doped AlGaN superlattice is compared. A three-fold increase of the output power was observed for LEDs with UV-transparent p-AlGaN layers. To investigate these findings, LEDs with low reflective Ni/Au and high reflective Al contacts are fabricated and characterized. Together with ray tracing simulations and detailed measurements of the metal reflectivities, we were able to determine the LEE and the internal quantum efficiency (IQE). According to on-wafer measurements, the external quantum efficiency (EQE) increases from 0.3% for an absorbing p-Al0.2Ga0.8N/Al0.4Ga0.6N-superlattice with Ni/Au contacts to 0.9% for a UV-transparent p-Al0.4Ga0.6N/Al0.6Ga0.4N-superlattice with Al contacts. This 3? enhancement of the EQE can be partially ascribed to an improved LEE (from 4.5% to 7.5%) in combination with a 1.8? increase of the IQE when using a p-Al0.4Ga0.6N/Al0.6Ga0.4N-superlattice instead of a p-Al0.2Ga0.8N/Al0.4Ga0.6N-superlattice.

10104-62, Session 14

Nonpolar and semipolar GaN/InGaN core-shell nanostructure LEDs *(Invited Paper)*

Daniel F. Feezell, Ashwin K. Rishinaramangalam, Mohsen Nami, Serdal Okur, Rhett F. Eller, Isaac Stricklin, Arman Rashidi, The Univ. of New Mexico (United States); Igal Brener, Center for Integrated Nanotechnologies (United States); Darryl M. Shima, Ganesh Balakrishnan, Christos G. Christodoulou, Steven R. J. Brueck, The Univ. of New Mexico (United States)

III-nitrides are the preferred materials for visible optoelectronics, including high-brightness light-emitting diodes (LEDs) for solid-state lighting, violet laser diodes for optical data storage, and blue and green laser diodes for projection systems. However, III-nitrides grown on the conventional polar c-plane using sapphire substrates suffer from polarization-related electric fields and high dislocation densities, which may degrade device performance. Growth on nonpolar and semipolar free-standing GaN is one option to address these issues, although this approach is associated with high substrate costs. Another option is to realize nonpolar and semipolar active regions using bottom-up nanoscale selective-area epitaxy (SAE) on sapphire substrates. The SAE technique leverages the natural differences in growth rates between various crystal facets to produce three-dimensional GaN/InGaN core-shell nanostructures with large nonpolar and semipolar surface areas and low dislocation densities on inexpensive substrates. In this work, we use SAE and metal organic chemical vapor deposition (MOCVD) to demonstrate electrically injected nonpolar and semipolar GaN/InGaN core-shell nanostructure LEDs based on nanowires and triangular nanostripes, respectively. We will discuss challenges and opportunities associated with the growth and fabrication of bottom-up nanostructure LEDs, including techniques to eliminate leakage current and the effects of the template configuration and growth conditions on emission wavelength and nanostructure geometry. We will also present data on internal quantum efficiency, carrier lifetime, optical polarization, and high-speed modulation of the core-shell nanostructure LEDs.

10104-63, Session 14

Semipolar InGaN-based superluminescent diodes for solid-state lighting and visible light communications

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III-nitride light emitters, such as light-emitting diodes (LEDs) and laser diodes (LDs), have been demonstrated and studied for solid-state lighting (SSL) and visible-light communication (VLC) applications. However, the performance of LED-based SSL-VLC system is limited by the “efficiency droop” and <100 MHz 3-dB bandwidth. InGaN-based LDs were recently studied as a droop-free, high-speed emitter, yet it is associated with speckle-noise and safety concerns. In this paper, we presented the semipolar-plane InGaN-based violet-blue emitting superluminescent diodes (SLDs) as a high-speed, high-brightness, and speckle-free light source, combining the advantages of LEDs and LDs.

The studied SLDs were fabricated using integrated passive absorber and tilted facet configurations, emitting in the violet-blue region. The 446-nm emitting SLD having a 490-μm absorber region and 1000-μm gain region showed a broad spectral linewidth of 8.4 nm at an injection current of 500 mA (6.67 kA/cm^2). The SLD generated > 200 mW optical power in the amplified spontaneous emission (ASE) regime and the phosphor-converted white light exhibited a color rendering index of 64.4 and a color temperature of 4094 K. A higher CRI might be achieved by using violet SLD exciting blue-green-red phosphor mixture. The 405-nm emitting SLD having a 590-μm long tilted facet configuration showed a spectral linewidth of 9 nm at 400 mA (16.9 kA/cm^2). With a large 3-dB bandwidth of ~800 MHz, the SLD enabled a data rate of 1.3 Gbps using on-off keying modulation scheme. The findings are significant in presenting SLD for SSL-VLC applications.

10104-64, Session 14

Direct comparison of structural and optical properties of a nitride-based core-shell microrod LED by means of highly spatially-resolved cathodoluminescence and u-Raman

Frank Bertram, Otto-von-Guericke-Univ. Magdeburg (Germany); Marcus Müller, Otto-von-Guericke Univ. Magdeburg (Germany); Peter Veit, Otto-von-Guericke-Univ. Magdeburg (Germany); Christian Nenstiel, Gordon Callsen, Technische Univ. Berlin (Germany); Matin Mohajerani, Jana Hartmann, Hao Zhou, Hergo-Heinrich Wehmann, Technische Univ. Braunschweig (Germany); Axel Hoffmann, Technische Univ. Berlin (Germany); Andreas Waag, Technische Univ. Braunschweig (Germany); Jürgen H. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

We present a nanometer-scale correlation of the structural, optical, and electronic properties of InGaN/GaN core-shell microrod LEDs: The microrods were fabricated by MOVPE on a GaN/sapphire template covered with an SiO2-mask. Through the mask openings, Si-doped n-GaN cores were grown with high SiH4 flow rate at the base. Subsequently, the SiH4 flow rate was reduced towards the microrod tip to maintain a high surface quality. The Si-doped GaN core was finally encased by an InGaN single quantum well (SQW) followed by an intrinsic GaN layer and a thick Mg-doped p-GaN shell.

Highly spatially resolved cathodoluminescence (CL) directly performed in a scanning transmission electron microscope (STEM) was applied to analyze the free-carrier concentration within the Si-doped GaN core and the luminescence properties of the individual functional layers. The CL was supported by Raman spectroscopy directly carried out at the same microrod on the thin TEM-lamella.

The cross-sectional CL of a single microrod resolves the emission of the single layers. CL and Raman measurements reveal a high free-carrier concentration of 7x1019 cm 3 in the bottom part and a decreasing doping level towards the tip of the microrod. Moreover, structural investigations exhibit that initial Si-doping of the core has a strong influence on the

formation of extended defects in the overgrown shells. However, we observe the most intense emission coming from the InGaN QW on the non-polar side walls, which shows a strong red shift along the facet in growth direction due to an increased QW thickness accompanied by an increased indium concentration right at the intersection of generated defects and InGaN QW, a red shifted emission appears, which indicates indium clustering.

10104-65, Session 14

Novel device designs enabled by lattice-matched GaN-ZnGeN2 heterostructures

Hongping Zhao, Lu Han, Case Western Reserve Univ. (United States)

Group III-nitride (Al-, In-, Ga-, N) material system has been well studied and widely applied in optoelectronics such as light emitting diodes (LEDs) for solid state lighting. In contrast, the group II-IV-nitride is rarely studied, yet it can expand the material properties provided by III-nitrides. For example, ZnGeN2 has a similar bandgap and lattice constant as those of GaN. Recently, theoretical studies based on first principle calculation indicate a large band offset between GaN and ZnGeN2 (Delta_Ec=1.4 eV; Delta_Ev=1.5 eV). Utilizing the novel heterostructures of GaN (InGaN)/ZnGeN2, we studied the following two types of device structures: 1) Type-II InGaN-ZnGeN2 quantum wells (QWs) for high efficiency blue and green LEDs; 2) Lattice-matched GaN-ZnGeN2 coupled QWs for near-IR intersubband transitions. The design of type-II InGaN-ZnGeN2 QWs leads to a significant enhancement of the electron-hole wavefunction overlap due to the strong confinement of the holes in the ZnGeN2 layer as well as the engineered band bending. Simulation studies based on a self-consistent 6-band k?p method indicate an enhancement of 5-7 times of spontaneous emission rate for an appropriately designed type-II InGaN-ZnGeN2 QWs for LED applications. For the coupled QW structure, it is comprised of two GaN QWs separated by a thin ZnGeN2 barrier layer, with thick ZnGeN2 layers as outer barriers surrounding the QWs. Our studies indicate that with optimized ZnGeN2 barrier thickness, the energy separation between E1 and E2 can be tuned to 92 meV for the resonance of the electron and LO-phonon scattering.

10104-66, Session 14

Gallium nitride light sources for optical coherence tomography

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The advent of optical coherence tomography (OCT) has permitted high-resolution, non-invasive, in vivo imaging of the eye, skin and other biological tissue. The axial resolution is limited by source bandwidth and central wavelength. With the growing demand for short wavelength imaging, super-continuum sources and non-linear fibre-based light sources have been demonstrated in tissue imaging applications exploiting the near-UV and visible spectrum. Whilst the potential has been identified of using gallium nitride devices due to relative maturity of laser technology, there have been limited reports on using such low cost, robust devices in imaging systems.

A GaN super-luminescent light emitting diode (SLED) was first reported in 2009, using tilted facets to suppress lasing, with the focus since on high power, low speckle and relatively low bandwidth applications. In this paper we discuss several methods of producing GaN based broadband sources, including the use of angled facets and an absorber to suppress lasing, with the merits of either a passive or grounded absorber discussed with regards to broad-bandwidth applications, rather than power applications.

For the first time in GaN devices, the performance of the light sources developed are assessed though the point spread function (PSF) (which describes an imaging systems response to a point source), calculated from the emission spectra, which is then compared to the interference pattern obtained using an interferometer. We show a sub-6μm resolution is possible without the use of special epitaxial techniques, ultimately outlining the suitability of these short wavelength, broadband, GaN devices for use in OCT applications.

10104-67, Session 15

InGaN-based flexible light-emitting diodes *(Invited Paper)*

Can Bayram, Univ. of Illinois at Urbana-Champaign (United States)

Novel layer release and transfer technology of single-crystalline GaN semiconductors is attractive for enabling many novel applications including flexible photonics and hybrid device integration. To date, LED research has been primarily focused on rigid devices due to the thick growth substrate. This prevented fundamental research in flexible inorganic LEDs, and limited the applications of LEDs in the solid state lighting (due to the substrate cost) and in optogenetics (due to LED rigidness). In the literature, a number of methods to achieve layer transfer have been reported including the laser lift-off, chemical lift-off, and Smartcut. However, the release of films of GaN semiconductors has been challenging since their elastic moduli and chemical resistivity are much higher than most conventional semiconductors. In this talk, we are going to review the existing technologies and propose a new mechanical release technique to overcome these problems.

10104-68, Session 15

8-inch GaN on Si-based wafer-level chip-scale package *(Invited Paper)*

Jun-Youn Kim, SAMSUNG Electronics Co., Ltd. (Korea, Republic of)

To reduce the $/lm for GaN-based LEDs, most LED makers are adopting flip-chip based Chip Scale Packaging (CSP) technology. However, it is difficult to realize true wafer-level (WL) CSP technology with conventional sapphire substrates caused by “blue light leak” issue. On the other hand, thin-film flip-chip technology practically eliminates blue light leak and allows a simpler process of phosphor coating and dicing.

To maximize the advantages of WL-CSP, large diameter process is necessary for it to be cost effective. In this sense, 8 inch Si wafer is the best candidate. GaN-on-Si based LEDs, however, have seen little growth in the lighting market due to several issues that hamper the efficiency and reliability related to the quality of GaN films grown on Si. However, we have overcome all drawbacks including yield, device reliability and LM-80 by proprietary stress-managed buffer and optimized LED epitaxial structure. In addition to the comparable efficiency and reliability performance, we discovered several other advantages of using 8 inch Si substrates such as the wavelength uniformity, low thermal droop and low compressive strain of MQW.

Wafer-level chip scale package (WL-CSP) on silicon substrates has its own set of advantages such as relatively easier to texture the GaN or phosphor surface at the wafer level to maximize photon extraction efficiency and multi-layer phosphor coating to further push the efficiency upwards.

10104-69, Session 15

Origin of the high series resistance in InGaN-based blue light-emitting diodes

Jong-In Shim, Dong-Pyo Han, Dong-Soo Shin, Hanyang Univ. (Korea, Republic of); Kyu-Sang Kim, Sangji Univ. (Korea, Republic of)

Although the performances of InGaN-based light-emitting diodes (LEDs) have significantly improved so far, a higher wall-plug efficiency (WPE) is still desired. Improving the WPE requires enhancing the internal quantum efficiency (IQE) and reducing the forward voltage (VF) simultaneously. While it has been recognized experimentally that both the IQE and the VF are interactively dependent on epitaxial growth conditions, they have been studied independently as the so-called "efficiency droop" and the ohmic problem.

Recently, we have introduced an analysis technique of combining the IQE and VF curves, in which the radiative and nonradiative recombination currents are plotted and analyzed separately as a function of applied voltage. Based on this technique, it has been found that the radiative recombination current does follow the ideal Shockley diode equation with an ideality factor of 1 and a constant series resistance Rr. In fact, Rr varies with epitaxial growth conditions of multiple-quantum-well (MQW) active regions and its relatively high values cannot be explained simply by the ohmic properties in metal and bulk epitaxial layers. In order to clarify the issue, we analyze the carrier energy-loss mechanisms inside and outside the MQW region including the ohmic loss, the optical absorption, the Shockley-Read-Hall (SRH) recombination, and carrier heating/cooling effects. Analysis results on a blue LED reveals that the carrier accumulation and subsequent spill-over from the MQWs to the outside region due to insufficient carrier recombination rates is the most probable mechanism of explaining such a constant and relatively high series resistance in current-voltage curves in blue LEDs.

10104-70, Session 15

Characteristics of radiative recombination current in semiconductor quantum-well light-emitting diodes in association with the ideality factor

Gyeong Won Lee, Hanyang Univ (Korea, Republic of); Dong-Soo Shin, Jong-In Shim, Chan-Hyoung Oh, Hanyang Univ. (Korea, Republic of)

While the radiative recombination current holds the key in semiconductor light-emitting diodes (LEDs), it has been typically assumed to be understood completely and little attention has been paid. A simple analysis based on the ABC model suggests that the radiative recombination current should obey the ideal Shockley equation with an ideality factor of 1. With the modern semiconductor LEDs utilizing the multiple quantum wells (MQWs), it is not clear whether this simple analysis holds and gives a constant ideality factor. In this paper, we use InGaN-based MQW LEDs with different wavelengths to analyze the radiative recombination current to clarify the issue further. In order to separate the radiative recombination current from the total device current, we measure the internal quantum efficiency of the device by using the temperature-dependent electroluminescence. Then the radiative recombination current is obtained by multiplying the internal quantum efficiency with the total current. We demonstrate that even in the LEDs with MQW active regions such as InGaN-based blue LEDs, the radiative recombination current still obeys the Shockley equation. Useful information that we can obtain from the analysis of the radiative recombination current is also discussed.

10104-71, Session 15

Processing and characterization of high-resolution GaN/InGaN LED arrays at 10 micron pitch for micro display applications

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We report the fabrication process and characterization of high resolution 873 x 500 pixels emissive arrays based on blue or green GaN/InGaN light emitting diodes (LEDs) at a reduced pixel pitch of 10 µm. A self-aligned process along with a combination of damascene metallization steps is presented as the key to create a common cathode which is expected to provide good thermal dissipation and prevent voltage drops between center and side of the micro LED matrix. We will discuss the challenges of a self-aligned technology related to the choice of a good P contact metal and will present our solutions for the realization of the metallic interconnections between the GaN contacts and the higher levels of metallization at such a small pixel pitch. Enhanced control of each technological step allows scalability of the process up to 4 inch LED wafers and production of high quality LED arrays. The very high brightness (up to 2.107 Cd.m-2) and good external quantum efficiency (EQE) of the resulting device make these kind of micro displays suitable for augmented reality or head up display applications.

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10105-51, Session 1

Why is Tc in cuprates so high? *(Keynote Presentation)*

Ivan Bozovic, Brookhaven National Lab. (United States) and Yale Univ. (United States); X. He, Yale Univ. (United States); J. Wu, Anthony T. Bollinger, Brookhaven National Lab. (United States)

We use atomic-layer-by-layer molecular beam epitaxy to synthesize atomically perfect thin films and multilayers of high-Tc cuprates. Using a continuous spread in composition we tune the doping level in steps of 0.01%. We use high-throughput measurements on combinatorial libraries to study magneto-resistance and Hall effect and measure accurately the coherence length [xi]. We measure the absolute value of penetration depth [lambda] to accuracy better than 1%.

Here we review the results of a comprehensive study that took ten years and thousands of cuprate samples. The large statistics reveals clear trends and intrinsic properties; this is es-sential when dealing with complex materials such as cuprates. We have measured the key physical parameters (Tc, [lambda], and [xi]) of the superconducting state and established their precise dependence on doping, temperature, and external fields. The findings bring in some great surprises, challenge the commonly held beliefs, rule out many models, and answer our initial question.

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10105-50, Session 2

Large bipolarons and oxide superconductivity *(Invited Paper)*

David Emin, The Univ. of New Mexico (United States)

Large-bipolaronic superconductivity is plausible with carrier densities below those of conventional metals. Bipolarons form when carriers self-trap in pairs. Coherently moving large-bipolarons require extremely large ratios of static to optical dielectric-constants. The mutual Coulomb repulsion of a planar large-bipolaron's paired carriers drives it to a four-lobed shape. A phonon-mediated attraction among large-bipolarons propels their condensation into a liquid. This liquid's excitations move slowly with huge effective masses. Excitations' concomitant weak scattering by phonons produces a moderate low-temperature resistivity that increases linearly with rising temperature. With falling temperature a "gap" widens between large-bipolarons' excitations and those of their self-trapped electronic carriers.

10105-53, Session 2

Title to be determined *(Invited Paper)*

Chang-Beom Eom, Univ. of Wisconsin-Madison (United States)

No Abstract Available

10105-75, Session 2

Nanoclusters as a new family of high temperature superconductors *(Invited Paper)*

Avik Halder, Argonne National Lab. (United States) and The Univ. of Southern California (United States); Vitaly V. Kresin, The Univ. of Southern California (United States)

Electrons in metal clusters organize into quantum shells, akin to atomic shells in the periodic table. Such nanoparticles are referred to as "superatoms". The electronic shell levels are highly degenerate giving rise to sharp peaks in the density of states, which can enable exceptionally strong electron pairing in certain clusters containing tens to hundreds of atoms.

A spectroscopic investigation of size – resolved aluminum nanoclusters has revealed a sharp rise in the density of states near the Fermi level as the temperature decreases towards 100 K. The effect is especially prominent in the closed-shell "magic" cluster Al66 [1, 2]. The characteristics of this behavior are fully consistent with a pairing transition, implying a high temperature superconducting state with Tc > 100K. This value exceeds that of bulk aluminum by two orders of magnitude.

As a new class of high-temperature superconductors, such metal nanocluster particles are promising building blocks for high-Tc materials, devices, and networks.

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10105-78, Session 2

Probing superconducting transition in underdoped La2-xSrxCuO4 by low-temperature resistance noise spectroscopy *(Invited Paper)*

Xiaoyan Shi, The Univ. of Texas at Dallas (United States); Zhenzhong Shi, Dragana Popovi?, National High Magnetic Field Lab. (United States)

We report the resistance noise spectroscopy technique and its applications in detecting the nature of superconducting transistion in high transition temperature cuprates. In underdoped La2-xSrxCuO4 thin films, where interlayer coupling is relatively weak and thus the system is effectively two-dimensional [1], resistance noise spectroscopy shows the first experimental evidence of correlated dynamics near the superconducting transition of the Berezinskii-Kosterlitz-Thouless type. In addition, resistance fluctuations in the low-temperature ordered phase are correlated, slow and breaking ergodicity, which means the system exhibits properties that cannot be fully detected in any reasonable experimental time frame [2].

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10105-81, Session 2

Superconductivity and magnetism at high Tc cuprate-CMR manganite interface *(Invited Paper)*

Jak Chakhalian, Rutgers, The State Univ. of New Jersey (United States)

Oxide interfaces offer a rich variety of physics and a pathway to create new classes of functional oxide materials. The interface between the cuprate high-temperature superconductors and ferromagnetic manganites is of particular interest due to the strongly antagonistic nature of the superconducting and ferromagnetic phases. Advancements in the synthesis of oxide heterostructure offers the opportunity to merge these two dissimilar oxides with atomic precision to understand the fundamental limits of bringing such states into close proximity. However, the main challenge is to understand the physical framework that describes the behavior of strongly correlated electrons near oxide interfaces. One aspect that will be addressed here is the use of advanced tools to gain detailed electronic and magnetic information from the boundary region[1-3]. In this talk, recent work will be addressed both from the visualization of the interface with spatially resolved tools [3] as well as harnessing layer-by-layer growth to explore the limits in ultrathin superlattices[4]. These insights allow us to better understand the physics behind the interfacial spin and orbital reconstruction observed in this system[1-4].

1. J. Chakhalian et. al. Nature Physics 2, 244 (2006).

2. J. Chakhalian et. al. Science 318, 1114 (2007).

3. Te-Yu Chien et al. Nature Communications 4 2236 (2013).

4. B. Gray et al, Scientific Reports 6, 33184 (2016); doi:10.1038/srep33184.

10105-49, Session 3

BCS vs BEC in High-Tc oxides and related superconductors *(Invited Paper)*

Davor Pavuna, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Following years of studies of sample preparation, doping, intrinisc and deliberate disorder as well as the role of strain in high-Tc oxides, we have performed systematic experiments* with ionic liquid gating on cuprates and related materials. We were able to substantially vary Tc with the applied electric field and have observed striking quantum phase transition in LSCO films [1]. Hence, we note that 105 years after the discovery of superconductivity and 30 years after the discovery of high-Tc in cuprates we still have essentially the BCS physical picture for low-Tc materials while for high-Tc, there are several scenarios. From our data, and independent results of other groups, it is clearly established that there are 2e-to-2e local(ized) pairs in an insulator. Moreover, precise characterization and susceptibility measurements on more than 2000 cuprate films [2] clearly indicate that an alternative approach is also necessary. Specifically, we note numerous proposals that consider the possibility of local pairing*. We provide an up-to-date critical discussion on BCS vs BEC models and emerging underlying physics in superconducting oxides and related new high-Tc quantum materials.

[1] Guy Dubuy, EPFL doctoral Thesis (2014)

[2] Ivan Bozovic et al., Nature (2016)

* In collaboration with Ivan Bozovic et al. 2,3

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10105-72, Session 3

Photoconductivity and carrier recombination in insulating cuprates *(Invited Paper)*

Derek G. Sahota, Simon Fraser Univ. (Canada); Jesse C. Petersen, Univ. of Oxford (United Kingdom); Amir D. Farahani, Simon Fraser Univ. (Canada); Ruixing Liang, The Univ. of British Columbia (Canada) and Canadian Institute for Advanced Research (Canada); Hanna A. Dabkowska, McMaster Univ. (Canada); Graeme Luke, McMaster Univ. (Canada) and Canadian Institute for Advanced Research, Toronto (Canada); J. Steven Dodge, Simon Fraser Univ. (Canada) and Canadian Institute for Advanced Research, Toronto (Canada)

We establish a detailed phenomenology of photocarrier transport in the copper oxide plane by studying transient photoconductivity and recombination dynamics in the insulating copper oxides $Sr_2CuO_2Cl_2$, $YBa_2Cu_3O_6$, and La_2CuO_4. We observe a common dependence of the photoconductivity and carrier recombination on time, fluence, and temperature. We infer an intrinsic photocarrier mobility of μ~0.5 cm2/V·s from the peak photoconductivity, comparable to the mobility exhibited by chemically doped materials. The initial photoconductivity decay rate is independent of fluence, indicating a lack of interaction among photoexcitations. We show that the temperature dependence may be associated with scattering from thermal excitations. We observe a crossover with time, to a thermalized regime characterized by hopping conductivity with low activation energy. Our results indicate that photocarriers move relatively freely in a nonequilibrium phonon-magnon cloud at early times, then become trapped by disorder as the cloud dissipates into a thermal distribution.

10105-74, Session 3

Strong off-diagonal polarizability and electron-lattice coupling in high-temperature superconductors *(Invited Paper)*

Adrian Gozar, Yale Univ. (United States); Peter Abbamonte, Univ. of Illinois at Urbana-Champaign (United States); Ivan Bozovic, Brookhaven National Lab. (United States) and Yale Univ. (United States)

High-temperature superconducting (HTS) cuprates are highly anisotropic materials which exhibit metallic-like behavior in the CuO_2 planes while retaining dielectric properties in the perpendicular, c-axis, direction. Experimental data show however that in HTS systems the in-plane electronic excitations are strongly coupled to c-axis polarized vibrations. This interaction is manifest in various settings, for example in the resonant Raman profile of phononic excitations, inelastic quasiparticle tunneling, as observation of notch-like features and forbidden scattering for in-plane optical conductivity, colossal c-axis photo-expansion upon in-plane illumination as well as in high-resolution electron energy-loss spectra. We propose that this anisotropic coupling is driven by strong unscreened Coulomb interactions and the preponderance of the Madelung component to the cohesion energy, in particular by the large inter-atomic displacements induced by charge redistribution within the CuO_2 planes.

10105-83, Session 3

Superconductivity in In-doped SnTe nanostructures *(Invited Paper)*

P. Kumaravadivel, Yale Univ. (United States) and Energy Sciences Institute (United States); G. Pan, Yale Univ. (United States); Y. Zhou, Judy J. Cha, Yale Univ. (United States) and Energy Sciences Institute (United States)

Topological insulators (TIs) and topological crystalline insulators (TCIs) are unique states of matter with an insulating bulk and gapless surface states (SS) that are chiral and massless. A derivative of these topological materials – the topological superconductor (TSC) has garnered great interest especially for topological quantum information processors. While the physics of TIs, TCIs and TSCs has been well established, realizing the full potential of these materials relies on the capability of synthesizing high quality, scalable nanostructures. A main challenge for synthesis is having the bulk states sufficiently gapped so that the unique electronic signatures of the SS can emerge in electronic transport studies. In this work, we address and successfully accomplish a crucial step in the synthesis by growing In-doped SnTe nanowires and nanoribbons which show superconductivity. For this purpose we employ the chemical vapor deposition (CVD) method using Au nanoparticles as catalyst. We find that the superconducting transition varies across different morphologies. Nanoplates show a complete and sharp resistance drop at the superconducting transition temperature (Tc) whereas nanoribbons show a more gradual transition at a slightly lower Tc. In some nanoribbons we observe a saturating resistance and signs of multiple Tc's within the same nanostructure.

10105-84, Session 3

Title to be determined *(Invited Paper)*

Wei Ku, Shanghai Jiao Tong Univ. (China)

No Abstract Available

10105-1, Session 4

High performance amorphous Zn-Sn-O: impact of composition, microstructure, and thermal treatments in the optoelectronic properties *(Invited Paper)*

Monica Morales-Masis, Quentin Jeangros, Esteban Rucavado, Federica Landuchi, Aicha Hessler-Wyser, Christophe Ballif, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Zinc and Tin oxides are both earth-abundant materials with demonstrated applicability as electrodes in several optoelectronic devices. The presence of grain boundaries in these polycrystalline films generally limits the electron mobility. By a combinatorial study of ZnO and SnO2, we have developed a transparent conducting amorphous zinc tin oxide (ZTO) electrode, free of grain boundaries, with a dense (void-free) microstructure. We show how tuning the stoichiometry (Zn4.5Sn30.2O65.3) and film's microstructure during sputtering deposition, allows achieving electron mobilities up to 25 cm2/Vs, for free carrier concentrations of ~ 7 x 1019 cm-3. The effects of post-deposition thermal treatments are furthermore studied. We show that the ZTO films remain stable up to 600 °C annealing in air, keeping their dense amorphous microstructure, as confirmed by cross-section TEM and XRD, while presenting improved electron mobility up to 35 cm2/Vs. We propose that the improvement in mobility is linked to the passivation of defects, these being uncoordinated Sn atoms, which create sub-gap states, widening the band edge absorption. The optoelectronic properties of ZTO are furthermore compared with amorphous indium-based TCOs, as hydrogenated indium oxide and indium zinc oxide, in terms of density of sub-gap defects, Urbach energy, carrier transport mechanisms, chemical and thermal stability. While the amorphous indium-based electrodes present higher mobilities and lower sub-gap absorption, the ZTO electrodes have much higher thermal and chemical stability. The application of ZTO in large-area flexible OLEDs is successfully demonstrated, representing a significant step forward in the development of high performance indium-free electrodes.

10105-2, Session 4

Conformal and doping-tunable conducting oxide coatings for infrared plasmonics *(Invited Paper)*

Justin W. Cleary, Air Force Research Lab. (United States); Ricky Gibson, Evan M. Smith, Shiva Vangala, Air Force Research Lab. (United States) and Wyle Labs. (United States); Isaiah O. Oladeji, SISOM Thin Films, LLC (United States); Farnood Khalilzadeh-Rezaie, Robert E. Peale, Univ. of Central Florida (United States)

In recent years, infrared plasmonics has turned towards materials that are wavelength and application tailorable, and which are geared towards CMOS processing. The transparent conductive oxides are very favorable towards infrared plasmonic applications for a number of reasons, one of which being the natural visible transparency due to their relatively large bandgap. Fluorine-doped tin oxide (FTO) is one such transparent and doping-tunable material that in addition is low cost due to spray deposition techniques that result in perfectly conformal coatings. First we will present results related to morphology, optical properties, and electrical characteristics of chemical spray FTO films as a function of F/Sn ratio and temperature of substrate during deposition. These films are characterized via scanning electron microscopy, infrared ellipsometry, x-ray diffraction, four-point probe, Hall measurements, and contactless resistivity mapping. A deposition recipe that resulted in relatively small resistivity and high carrier concentration is then down-selected for demonstration of surface-plasmon excitation. 1D gratings with a range of structural parameters are etched into silicon and coated with a thin oxide. These gratings are then conformally coated with FTO. Photonic-to-plasmonic coupling is demonstrated with these gratings in the mid-wave and long-wave infrared with the results agreeing with theory. The work presented here could play a key role in novel decreased-cost detectors, filters, and on-chip optoelectronics.

10105-3, Session 4

Doping, co-doping, and defect effects on the plasmonic activity of ZnO-based transparent conductive oxides

Arrigo Calzolari, Istituto Nanoscienze (Italy); Alice Ruini, Univ. degli Studi di Modena e Reggio Emilia (Italy); Alessandra Catellani, Istituto Nanoscienze (Italy)

Transparent conducting oxides (TCOs) are electrical conductive materials with a low absorption of light in the visible range. The unique combination of metallicity and transparency makes TCOs appealing for a variety of applications, including photovoltaics, flat displays, invisible electronics and plasmonics. TCOs are obtained by doping wide band-gap semiconductors with metal ions. Yet, the remarkable combination of conductivity in an albeit wide-gap material is not fully understood.

Here, we present a first principles investigation of the optical and plasmonic properties of metal-doped ZnO systems (MZO), based on density functional theory. We investigate how doping [1] and defects [2] affects the optoelectronic properties of MZOs, as TCO materials. While most TCOs are n-type, we then consider the effects of cooping and deactivation processes

to obtain p-type ZnO TCOs.

Finally, we study the origin of plasmonic activity in MZO [3-4] and we provide a microscopic insight on the formation of surface-plasmon polaritons at the Al:ZnO/ZnO interfaces in terms of characteristic lengths that can be measured by experiments. These systems present tunable plasmonic activity in the near-IR range and in particular at wavelength relevant for telecommunications (1,5 ?m), in agreement with the experimental results.

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10105-4, Session 4

Model-free determination of optical constants in bulk transparent conductive oxides

David C. Look, Wright State Univ. (United States) and Air Force Research Lab. (United States) and Wyle Labs. (United States); Buguo Wang, Wright State Univ. (United States)

Transparent conductive oxides (TCOs) are widely used as thin films or substrates and thus it is important to have accurate values of their optical constants: absorption and reflection coefficients, ? and R; or equivalently, index of refraction components eta and kappa , n = eta + i x kappa. Generally, such knowledge is obtained by using dielectric models to fit the wavelength dependence of the measured reflectance Rmeas, or transmittance Tmeas, or the ellipsometric parameters Delta-meas and Psi-meas. Indeed, such procedures are necessary for analysis of multilayer structures, but, interestingly, not for single slabs of uniform material, such as substrates. For the latter, we derive equations for alpha, R, eta, and kappa in terms of Tmeas and Rmeas. First R is calculated and then ? = -(1/d)ln[(1 – R – Ameas)/(1 – R – RAmeas)], where Ameas = 1 – Rmeas – Tmeas. No models or fitting procedures or approximations are necessary. In present practice, ? is usually determined from Tmeas(alpha,R) alone by invoking the approximation R = Rmeas. However, this approximation is valid only in highly-absorptive regions which may be only a small portion of the measured spectrum. Here, we calculate accurate optical constants in bulk ZnO, SrTiO3, MgO, and Ga2O3 over the range 190 – 3200 nm.

10105-5, Session 4

Tailoring the refractive index of ITO thin films by genetic algorithm optimization of the reactive DC-sputtering parameters

Elnaz Afsharipour, Cyrus Shafai, Univ. of Manitoba (Canada)

The variation of oxygen concentration in the Indium Tin Oxide (ITO) structure highly impacts its electrical and optical characteristics. In this work, we investigated the effect of oxygen concentration (O2/O2+Ar) and deposition pressure (p) on the refractive index (n) of reactive sputtered ITO thin films. A Genetic Algorithm (GA) technique was implemented to find optimal deposition conditions for obtaining every particular refractive index. Several samples of ITO thin film were deposited by DC sputtering technique in various oxygen concentrations and deposition pressures, to make the fitness function of GA. The quality of deposited ITO was evaluated by Haacke's Figure of Merit (FOM) (?Transmittance?^10/Resistance) and only samples with FOM>0.1 (10^-2 ?^-1), that shows both high transmission and low resistivity, were proceeded in the experiment. The refractive index of kept samples was in the range of 1.69 to 2.1. A linear polynomial surface was fitted to the data of O2/O2+Ar, p, and n of deposited films. The found relationship was then used as the fitness function of the GA. By defining the desired n as the objective value of the GA, the optimized deposition conditions for n =2.2 were found to be O2/O2+Ar = 1.5% at p=3.5 mTorr, and for n=1.6, to be O2/O2+Ar = 0.4%, at p=11 mTorr. The data was then validated by depositing ITO films in the calculated conditions which resulted in ITO films with predicted refractive indices (n=2.2 and n=1.6). Tailoring the refractive index of ITO is important in applications like distributed Bragg reflectors.

10105-77, Session 4

Zn-vacancy related defects in ZnO grown by pulsed laser deposition *(Invited Paper)*

Francis C. Ling, C. Q. Liu, Z. L. Wang, The Univ. of Hong Kong (Hong Kong, China); W. Anwand, Andreas Wagner, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

Undoped and Ga-doped ZnO (002) films were grown c-sapphire using the pulsed laser deposition (PLD) method. Zn-vacancy related defects in the films were studied by different positron annihilation spectroscopy (PAS). These included Doppler broadening spectroscopy (DBS) employing a continuous monenergetic positron beam, and positron lifetime spectroscopy using a pulsed monoenergetic positron beam attached to an electron linear accelerator. Two kinds of Zn-vacancy related defects namely a monovacancy and a divacancy were identified in the films. In as-grown undoped samples grown with relatively low oxygen pressure P(O2)≤1.3 Pa, monovacancy is the dominant Zn-vacancy related defect. Annealing these samples at 900 oC induced Zn out-diffusion into the substrate and converted the monovacancy to divacancy. For the undoped samples grown with high P(O2)=5 Pa irrespective of the annealing temperature and the as-grown degenerate Ga-doped sample (n≈1020 cm-3), divacancy is the dominant Zn-vacancy related defect. The clustering of vacancy will be discussed.

10105-6, Session 5

Quaternary BeMgZnO by plasma-enhanced molecular beam epitaxy for BeMgZnO/ZnO heterostructure devices *(Invited Paper)*

Umit Ozgur, Vitaliy Avrutin, Md Barkat Ullah, Mykyta Toporkov, Virginia Commonwealth Univ. (United States); Pierre Ruterana, CIMAP, UMR 6252 CNRS (France); David J. Smith, Arizona State University (United States); Hadis Morkoç, Virginia Commonwealth Univ. (United States)

No Abstract Available

10105-7, Session 5

Exceptional points in anisotropic photonic structures: from non-Hermitian physics to possible device applications *(Invited Paper)*

Marius Grundmann, Steffen Richter, Tom Michalsky, Chris Sturm, Univ. Leipzig (Germany); Jesús Zúñiga-Pérez, CNRS-CRHEA (France); Rüdiger Schmidt-Grund, Univ. Leipzig (Germany)

No Abstract Available

10105-8, Session 5

Oxide-based Materials by Atomic Layer Deposition *(Invited Paper)*

Marek Godlewski, Rafa? Pietruszka, Jaros?aw Kaszewski, Bart?omiej S. Witkowski, Sylwia A. Giera?towska, ?ukasz Wachnicki, The Institute of Physics, Polish Academy of Sciences (Poland); Micha? Godlewski, Anna Slonska, Zdzis?aw Gajewski, Warsaw Univ. of Life Sciences SGGW (Poland)

Thin films of wide band-gap oxides grown by Atomic Layer Deposition (ALD) are suitable for a range of applications. ALD-grown high-k oxides are used as insulators in the electronic devices. Other applications of oxides, such as resistance switching materials in memories, channels in transparent transistors, or as elements of solar cells will be demonstrated. In photovoltaics ALD-grown layers are applied as anti-reflection films, whereas thin films of ZnO are tested as replacement of ITO. For many of potential applications it is important that ALD growth method allows deposition of high density and uniformity thin films at low temperature and on large surfaces, including structured ones. New applications in organic photovoltaics, electronics and optoelectronics is thus possible. In the talk ALD principles will be shortly introduced and examples of recent applications of oxides will be given. Considering new applications, the same layers (ZnO, Al2O3, TiO2, HfO2, ZrO2), as used in electronics, can also find applications in biology, medicine and food industry. These layers show antibacterial activity.

The research was partially supported by the National Centre for Research by “Maestro” grant (2012/06/A/ST7/00398).

10105-9, Session 5

X-chromism oxides for energy saving *(Invited Paper)*

Aline D. Rougier, Manuel Gaudon, Institut de Chimie de la Matière Condensée de Bordeaux (France)

Materials with tunable optical properties because of external means such as illumination, temperature, pressure, electric and magnetic fields, X-rays, ion-beam radiation, gases, or electrochemical potential have large potential. In particular, some of the main drivers of the research activity in this field are the reduction of energy consumption by smart controlling of light and heat transfer through windows, the demand of opto-electronic and medical industry for emitting and sensing devices, as well environmental technology to increase functionality of chromogenic devices. Among chromic materials, transition metal oxides are of particular interest thanks to diverse properties in relation with the multivalent nature of the cations.

Taking examples in the field of electrochromic and thermochromic oxides, our presentation will illustrate how one can optimize the chromic properties by tuning the structure, the morphology, the composition of materials as well as the device architectures. The chromic properties of tungsten, nickel and vanadium oxides will be largely discussed.

10105-11, Session 6

Non-polar ZnO/(Zn,Mg)O heterostructures for intersubband devices: novel applications with an old material system? *(Invited Paper)*

Jean-Michel Chauveau, Maxime Hugues, Nolwenn Le Biavan, Denis Lefebvre, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France); Miguel Montes Bajo, Julen Tamayo-Arriola, Adrián Hierro, Univ. Politécnica de Madrid (Spain); Patrick Quach, Arnaud Jollivet, Nathalie Isac, Adel Bousseksou, Maria Tchernycheva, François H. Julien, Univ. Paris-Sud 11 (France); Borislav Hinkov, Gottfried Strasser, Technische Univ. Wien (Austria); Romain Peretti, Giaccomo Scalari, Jérôme Faist, ETH Zürich (Switzerland)

The development of Zinc Oxide (ZnO)-based applications have been strongly limited due to the lack of reproducible p-type doping. Here we present novel opportunities in the field of unipolar oxide wide band gap semiconductors. First we have developed the growth of nonpolar ZnO/ZnMgO multiple quantum wells (MQWs) and then we demonstrate that the structural and optical properties of the MQWs are reaching the required level for intersubband devices in terms of defects, surface and interface roughness and doping. We will show and discuss the most recent results as, for instance, intersubband transitions which have been observed in such structures.

This “Zoterac” project has received funding from the European Union's Horizon 2020 research and

innovation programme under grant agreement No 665107

10105-12, Session 6

Mid-IR intersubband absorption in m-plane ZnO/ZnMgO MQWs *(Invited Paper)*

Miguel Montes Bajo, Julen Tamayo-Arriola, Jose María M. Ulloa, Univ. Politécnica de Madrid (Spain); Arnaud Jollivet, Nathalie Isac, Adel Bousseksou, Maria Tchernycheva, François H. Julien, Univ. Paris-Sud 11 (France); Romain Peretti, Jérôme Faist, ETH Zürich (Switzerland); Nolwenn Le Biavan, Maxime Hugues, Jean-Michel Chauveau, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France); Adrian Hierro, Univ. Politécnica de Madrid (Spain)

ZnO has great potential for the mid and far IR (THz) through the use of intersubband (ISB) transitions in MQWs, although exploiting these transitions requires great control of the epitaxial layers as well as of the physics involved. In this work we present an analysis of the ISB optical absorption from ZnO/ZnMgO multi-quantum-wells (MQWs) grown homoepitaxially by MBE on non-polar m-plane ZnO. The structures consist of 15-20 ZnO/ZnMgO QWs (30% Mg in the barrier) with varying QW thickness and doping concentrations. The MQWs were characterized under a 45º-bevelled multi-pass waveguide configuration allowing the observation of ISB transitions in the 3-5 µm region for p-polarized incident light. The absence of an internal electric field in these non-polar structures helps in the analysis of the electronic transition and, indeed, the observed ISB transition energies follow the expected behavior with varying QW thickness and doping. However, in order to fully model the ISB transitions many-body effects have to be accounted for and quantified correctly, specifically for the depolarization shift due to the plasmon. We will present a detailed analysis of some of these effects and how they can be modeled and correctly predict the ISB transitions in the ZnO-based MQWs.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 665107 (project ZOTERAC).

10105-13, Session 6

Phononic properties of oxide superlattices and multi-quantum-well heterostructures *(Invited Paper)*

Markus R. Wagner, Juan Sebastian Reparaz, Gordon Callsen, Felix Nippert, Thomas Kure, Axel Hoffmann, Technische Univ. Berlin (Germany); Maxime Hugues, Monique Teysseire, Benjamin Damilano, Jean-Michel Chauveau, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France)

We address the electronic, phononic, and thermal properties of oxide based superlattices and multi quantum well heterostructures. In the first part, we review the present understanding of phonon coupling and phonon propagation in superlattices and elucidate current research aspects of phonon coherence in these structure. Subsequently, we focus on the experimental study of MBE grown ZnO/ZnMgO multi quantum well heterostructures with varying Mg content, barrier thickness, quantum well thickness, and number of periods. In particular, we discuss how the controlled variation of these parameters affect the phonon dispersion relation and phonon propagation and their impact on the thermal properties.

10105-14, Session 6

Precise control of plasmonic resonance wavelengths from 1.0 to 3.7 microns in Zn0.97Ga0.03O *(Invited Paper)*

David C. Look, Wright State Univ. (United States); Kevin D. Leedy, Air Force Research Lab. (United States); Gordon J. Grzybowski, Wyle Labs. (United States); Bruce B. Claflin, Air Force Research Lab. (United States)

Transparent conductive oxides such as Ga-doped ZnO (GZO) have been proposed for plasmonic applications in the near-IR region because of low losses compared to those of the widely-used noble metals. By annealing PLD-grown GZO (3%Ga) in Ar for 10 min at temperatures TA = 300 – 650 deg C, we can control the plasmonic resonance wavelength lambda-res from 1.0 - 3.7 microns, which includes the important telecom wavelengths 1.3 and 1.55 microns. To understand the physical changes that occur during the annealing process, we have measured Hall mobility mu_H and concentration n and calculated donor ND and acceptor NA concentrations at each TA. Both ND and NA decrease up to TA = 625 deg C, but ND decreases faster, leading to higher mu and lower n. From previous studies we have shown that the dominant donor is Ga_Zn, and acceptor, V_Zn. We monitor the depth profiles of Ga by X-ray photoelectron spectroscopy, and obtain further information on mobility and concentration by fitting the strong, plasmon-induced reflectances with a Drude formalism that yields fitting parameters mu_opt and n_opt. Up to about TA = 625 C, mu_opt ~ mu_H and n_opt ~ n; however, above 650 deg C, mu_H << mu_opt, consistent with increasing grain-boundary scattering.

10105-15, Session 7

Mechanisms of the persistent luminescence in Cr3+:ZnGa2O4 transparent glass-ceramics *(Invited Paper)*

Bruno Viana, Victor Cataing, Morgane Pellerin, Atul Sontakke, Laurent Bient, Didier Gourier, Alberto Jose, Mathieu Allix, Ecole Nationale Supérieure de Chimie de Paris (France)

A persistent luminescent material presents light emission during a long time (i.e. minutes or hours) after stopping the excitation source. Here transparent glass-ceramic materials were elaborated via a simple heat treatment of the parent glass composition and the glass-ceramic could exhibits about 50 wt% of ZnGa2O4 nanocrystals with size in the order of 20-30 nm. These very small size nanophosphors present interesting long persistent luminescence and they can be excited both under UV and under LED excitation within the visible range. Red long-lasting luminescence arising from the whole sample volume is observed in the Cr3+ doped transparent glass-ceramics, opening the route to a wider range of performing applications for this famous zinc gallate persistent phosphor. Furthermore, we better understand the origin of the persistent luminescent properties of the nanomaterial using electron paramagnetic resonance in order to study the chromium environment, and by thermoluminescence to investigate trapping and detrapping processes. Comparison was also possible with NPs obtained by microwave assisted hydrothermal synthesis.

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10105-16, Session 7

Blue light emission from ZnO-graphene hybrid quantum dot

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One of a wide-bandgap semiconductor, Zinc oxide (ZnO) has a near ultraviolet bandgap (3.37 eV) and an exciton binding energy of 60 meV at room temperature (RT), and has several favorable properties, such as high electron mobility, high oscillator strength, and good transparency. In the photoluminescence (PL) spectra of ZnO nanoparticles, the near band edge ultraviolet (UV) emission at 378 nm relevant to direct bandgap of ZnO, and blue light emissions centered at 410, 435, and 465 nm corresponding to Zn interstitial (Zni) to valence band maximum (VBM), and to Zn vacancies (VZn) and green light emission at 540 nm corresponding to conduction band maximum (CBM) to oxygen vacancy (Vo). Ultra-small size quasi consolidated ZnO-graphene nanoparticles was synthesized in which graphene outer layer was chemically attached with ZnO inner core. After attaching graphene to ZnO, green emission completely disappeared whereas the intensity of blue emission was greatly increased. Enhanced blue emission could be well described by both fast electron transfer from CBM of ZnO to graphene having similar molecular energy level with Zni and transition to VBM and Vzn. Glass/ITO/PEDOT:PSS/poly-TPD/ZnO-graphene/Cs2CO3/Al were fabricated and showed the blue emission centered at 435 nm with FWHM of about 90 nm.

10105-17, Session 7

Optical and defect properties of CaSc2O4:Ce3+ phosphor with and without Mg2+ charge compensation

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CaSc2O4:Ce3+ is a material for white-light emitting diodes (wLEDs) due to overlapping Ce3+ 5d1 level and GaN emission. We derived the energy level diagram of lanthanide ions to conclude that 5d1 level is ~0.17 eV below conduction band. The emission intensity in CaSc2O4:Ce3+ is much lower than the traditional YAG:Ce3+. It could be due to charge mismatch (Ce3+ substitutes Ca2+) and in YAG:Ce3+ (Y3+substitutes Ce3+). To improve the photoluminescence (PL) output, we tested Mg2+ for charge compensation. The PL decreased further due to new detrimental defects. An energy level diagram is constructed to understand the charge trapping-detrapping mechanism.

10105-18, Session 7

Afterglow luminescence in sol-gel/Pechini grown oxide materials: persistence or phosphorescence process?

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Persistent luminescence and phosphorescence, both yields afterglow luminescence, but are completely different mechanisms. Persistent luminescence involves a slow thermal release of trapped electrons stored in defect states, whereas the phosphorescence is caused due to triplet to singlet transition [1,2]. Many persistent luminescence phosphors are based on oxide inorganic hosts, and exhibit long afterglow luminescence after ceasing the excitation. We observed intense and long afterglow luminescence in sol-gel/pechini grown inorganic oxides, and as a first interpretation thought to be due to persistence mechanism. However, some of these materials do not exhibit defect trap centers, and a detailed investigation suggested it is due to phosphorescence, but not the persistence. Phosphorescence is not common in inorganic solids, and that too at room temperature, and therefore usually misinterpreted as persistence luminescence [3]. Here we present a detailed methodology to distinguish phosphorescence from persistence luminescence in inorganic solids, and the process to harvest highly efficient long phosphorescence afterglow at room temperature.

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10105-21, Session 7

Visualization of plasmon-enhanced photocarrier generation in ZnO/Ag nanogratings

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ZnO has attracted growing research attention as a strong candidate material for various optoelectronic device applications. It is important to understand and control the interactions between surface plasmons (SPs) and charge carriers in metal-ZnO hybrid nanostructures to improve the optical characteristics. In this work, we fabricated ZnO/Ag nanogratings using patterned polymer and Si templates. Excitation of the surface plasmon polaritons (SPPs) well explained the optical reflectance and photoluminescence spectra of the ZnO/Ag nanogratings [1,2]. Nanoscopic mapping of surface photovoltage (SPV), i.e., changes in the surface potential under illumination, obtained by Kelvin probe force microscopy (KPFM) enabled us to investigate the local behaviors of the photo-generated carriers. The magnitude and relaxation time of the measured SPV depended on the wavelength and polarization of the incident light [3]. This showed that the SP excitation in the nanogratings directly affected the creation and recombination processes of the charge carriers. All of these results suggested that SPV measurements using KPFM should be very useful for studying the SP effects in metal/semiconductor hybrid nanostructures.

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10105-22, Session 7

Growth orientations and crystal structures of ZnO nanoneedles using Ag nanoparticles as catalyst in vapor-liquid-solid growth

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The controlling mechanism for determining the growth direction of a Ga-doped ZnO (GaZnO) nanoneedle (NN) by using an Ag nanoparticle (NP) as vapor-liquid-solid (VLS) growth catalyst is disclosed. It is found that the local Ag (111) orientation of the catalytic Ag portion in an Ag NP determines the ZnO (002) orientation of the grown GaZnO and hence the NN growth direction. The ZnO (002) plane of the grown GaZnO is always parallel with the Ag (111) planes of the Ag portions involved in VLS growth in either the top or bottom Ag NP of an NN. When GaN is used as NN growth template, at a sufficiently high temperature (350-450 degrees C), a small Ag NP can become a quasi-single crystal with its Ag (111) plane consistent with the GaN (002) plane and hence results in the growth of a vertical GaZnO NN. However, tilted NNs can be grown from a larger Ag NP or a cluster of Ag NP on GaN due to its non-uniform Ag (111) orientation distribution. At the early stage of GaZnO growth, GaZnO precipitation can be observed between Ag layers within an Ag NP, indicating the growth of a semiconductor on Ag. On other templates, like Si, sapphire, or silicon diode, single-crystal Ag NP cannot be formed such that GaZnO NNs of random orientations are grown.

10105-19, Session 8

Zinc oxide nanostructures and its nano-compounds for efficient visible light photo-catalytic processes *(Invited Paper)*

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Zinc oxide (ZnO) in its nanostructure form is a promising material for visible light emission and utilization in different energy efficient photocatalytic processes. We will first present on recent results on the effect of varying the molar ratio of the synthesis nutrients on visible light emission. Further we will use the optimized conditions from the molar ration experiments to vary the synthesis processing parameters like stirring time etc.. the effect of all these parameters in order to optimize he efficiency and control the emission spectrum are investigated using different complementary techniques. Cathodoluminescence (CL) is combined with photoluminescence (PL) and electroluminescence (EL) as the techniques to investigate and optimizes visible light emission from ZnO/GaN light emitting diode. We then show and discuss recent finding of the use of ZnO nanoparticles (NPs) for efficient

photo-degradation of toxic dyes using the visible spectra, namely with a wavelength up to 800 nm. In the end we show how ZnO nanorods (NRs) are used as the first template to be transferred to bismuth zinc vanadate (BiZn2VO6). The BiZn2VO6 is then used to demonstrate efficient and cost effective hydrogen production through water splitting.

10105-20, Session 8

Spectroscopic ellipsometric thermo-optical characterization of heterogeneous structures of thin TiO2-Al2O3 bi-layer films grown by atomic layer deposition (ALD)

Rizwan Ali, Muhammad Rizwan Saleem, Seppo Honkanen, Univ. of Eastern Finland (Finland)

The stability of uniform, amorphous and high quality optical thin films is vital to function properly for optoelectronics and photonic devices. The environmentally driven conditions such as temperature, humidity and pressure etc., have significant effect on the optical properties of thin films which subsequently deteriorate the uniformity, density, and ultimately stable operation & sensitivity of the precise optical devices. In this work we report on the reduction in the temperature-induced changes and their corresponding effects on the optical properties of amorphous and thin TiO2 films after depositing uniformly ultra-thin Al2O3 barrier-layer films by Atomic Layer Deposition (ALD) method. Owing to TiO2 films' super hydrophilic nature and surface defects, the refractive index of ~100 nm thick ALD–TiO2 films decreases with temperature which shows negative thermo-optic coefficients (TOCs). While amorphous ALD–Al2O3 films possess positive TOCs and exhibit the ability to withstand under naturally or driven harsh environmental conditions. We demonstrated the reduction in the permeability of water molecules on ALD–TiO2 films and surface defects by mean of depositing ultra-thin ALD–Al2O3 impermeable barrier-layers. The temperature dependent-optical constants of thin ALD-TiO2–Al2O3 bi-layer films have been measured by a Variable Angle Spectroscopic Ellipsometer (VASE), covering a wide spectral range of 380 ≤ ? ≤ 1800 nm at three different angles of incidence (59°, 67°, & 75°) with temperature range from 25–105 °C. The Cauchy model is used to design and retrieve temperature-dependent optical constants at a wavelength 640 nm using WVASE32 modeling tool. The temperature-dependent optical constants of ~100 nm thick ALD–TiO2 with over-layers of ALD–Al2O3 films (10–70 nm), constituting bi-layer structures are studied to evaluate TOCs using polynomial fitting algorithm. The investigated heterogeneous structures of ALD-TiO2–Al2O3 bi-layer films have potential applications in nanophotonics. The centralized resonance peak of Resonant Waveguide Gratings (RWGs) in varying thermal environment and bio-molecular sensors can be stabilized by appropriate selection of optical materials in terms of their TOCs.

10105-23, Session 8

Metal oxide nanoparticles used from optical sensors to biosensors *(Invited Paper)*

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In this paper we refer the work performed within i3N/CENIMAT in the area of functional metal oxide nanoparticles to be used in a wide range of applications, as it will be exemplified in the following text.

ZnO NPs - ZnO nanostructures have been produced either under microwave irradiation using low cost domestic microwave equipment or by conventional heating, both under hydrothermal conditions. X-ray diffraction, scanning electron microscopy, Fourier transform infrared spectroscopy, room/low temperature photoluminescence and Raman spectroscopy have been used to investigated the structure, morphology and optical properties of the produced ZnO nanorods. The hexagonal wurtzite structure has been identified, and a red-orange emission has been detected in the presence of UV irradiation for all the conditions studied. The as-prepared ZnO nanorods were test as a UV sensor on paper substrate, which lead to a fast response and a rapid recovery times, as well a sensitivity up to 10 indicating that these materials may have a high potential to be employed in low cost, disposable UV applications.

VO2 NPs - The capability to control in an smart way the infrared reflectance to environmental temperature variations, can be achieved with thermochromic materials like VO2. In this paper we report by the first time a new application of VO2 on ceramic tiles, aiming to control the reflected IR radiation on smart roofs and thus improving the energy efficiency as possible and reducing the carbon dioxide emissions. The VO2 NPs have been produced by hydrothermal synthesis, providing a new, quicker and cleanner production route. The superior thermochromic characteristics of VO2 nanoparticles in conjunction with this new application to a smart roof offers a great potential to regulate the energy in an intelligent way.

WO3 NPs - Electrochemically active bacteria have the capability to transfer electrons to cell exterior, a feature that is currently explored for important applications in bioremediation and biotechnology fields. However, the number of isolated and characterized EAB species is still very limited regarding their abundance in nature. Colorimetric detection has emerged recently as an attractive mean for fast identification and characterization of analytes based on the use of electrochromic materials. In this work, WO3 nanoparticles were synthesized by microwave assisted hydrothermal synthesis and used to functionalize non-treated regular copy-paper substrates. This allowed the production of a paper-based colorimetric sensor able to detect EABs in a simple, effective, low-cost and eco-friendly manner.

10105-79, Session 8

Free-standing undoped ZnO microtubes with rich and stable shallow acceptors

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Fabrication of reliable large-sized p-type ZnO is the major challenge to realise ZnO-based electronic device applications. Here we report a novel technique to grow high-quality free-standing undoped acceptor-rich ZnO (A-ZnO) microtubes with dimensions of ~100 ?m in diameter and 5 mm in length by optical vapour supersaturated precipitation. The A-ZnO exhibits long lifetimes (>1 year) against compensation/lattice-relaxation and the stable shallow acceptors with binding energy of ~127 meV are confirmed from Zn vacancies. The A-ZnO provides a possibility for a mimetic p-n homojunction diode with n+-ZnO:Sn. The diode threshold voltage, turn-on voltage, reverse saturated current and reverse breakdown voltage are 0.72 V, 1.90 V, <10 ?A and >15 V, respectively. The high concentrations of holes in A-ZnO and electrons in n+-ZnO make the dual diffusion possible to form a depletion layer. The A-ZnO also demonstrates quenching-free donor-acceptor-pairs (DAP) emission located in 390-414 nm with temperature of 270-470 K. Combining the temperature-dependent DAP violet emission with native green emission, the visible luminescence of A-ZnO microtube can be modulated in a wide region of colour space across white light. The present work opens new opportunities to achieve ZnO with rich and stable acceptors instead of p-ZnO for a variety of potential applications.

10105-24, Session 9

Exploiting systems on foil *(Invited Paper)*

Rodrigo Ferrão de Paiva Martins, Manuel João Mendes, Luís M. Pereira, Diana Gaspar, Pedro Barquinha, António Vicente, Hugo Águas, Elvira M. C. Fortunato, CENIMAT-

Ctr. de Investigacao em Materials (Portugal) and CEMOP/ Uninova (Portugal)

The growth interest of the Internet of Things and the use of the cloud data base concept require the use of eco-self-sustainable conformable multi-functional interfaces at low cost substrates. In this presentation we discuss the developments achieved at CEMOP/CENIMAT concerning the exploitation of functional low cost surfaces, such as paper, in MESA like devices architectures that besides exploiting the surface, it allows controlling the onset voltage of the transistors in abroad range of values. Apart from that we also will present data concerning the exploitation of paper as substrate to growth solar cell devices and super capacitors to harvesting the systems to be developed in such foils. The architecture and the working principles of these devices will be discussed. The simulated transfer characteristics of these devices under low and high drain to source voltages will be discussed and compared with the set of experimental results achieved.

10105-25, Session 9

Heterogeneous integration of low-temperature metal-oxide TFTs *(Invited Paper)*

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The range of circuit fabrication possibilities enabled by the metal-oxide thin-film transistor (MO-TFT) is unprecedented. Large-area deposition techniques and high electron mobility are behind their adoption in the display industry, and substrate agnosticism and low process temperatures incited a wave of flexible electronics research [1]. MO-TFT circuits can be fabricated directly onto materials ranging from semiconductor wafers to paper, and can comprise dissimilar device technologies as heterogeneous integrated circuits. Vacuum and solution-based processing has been used to realize circuits with enhancement- and depletion-mode (E/D) MO-TFTs, MO-TFTs combined with organic TFTs or carbon nanotubes, and even MO-TFTs integrated onto Si LSI back end of line (BEOL) interconnects [2]. Indeed, microelectronic systems with dissimilar tightly-integrated active device technologies can offer advantages in cost, size, weight, power, and performance when compared to multi-chip circuit board approaches. Although system complexity available from silicon CMOS is unrivaled, certain compound semiconductors (CS) are better suited for high-frequency or –power. To close this gap major DoD investments were directed to establish foundry processes for heterogeneous integration of various technologies on a common Si VLSI platform [3]. In a similar vein we are exploring relatively simple, low-cost strategies for adding functionality not to VLSI, but to the high-performance CS-based circuits themselves [4].

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10105-26, Session 9

Chlorine and oxygen plasma influence on nanoparticle formation and aggregation in metal oxide thin film transistors

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Despite recent advances in metal oxide thin-film transistor technology, there is no foundry process available yet for large-scale deployment of metal oxide electronics and photonics, as it is currently found for silicon based electronics and photonics. One of the biggest challenges of the metal oxide platform is the stability of the fabricated devices. Also, there is wide dispersion on the measured specifications of fabricated TFT, from lot-to-lot and from different research groups. This can be partially explained by the importance of the deposition method and its parameters, which determine thin film microstructure and thus its electrical properties. Furthermore, substrate pre-treatment is an important factor, as it may act as a template for material growth. Not so often mentioned, plasma processes can also affect the morphology of deposited films on further deposition steps, such as inducing nanoparticle formation, which strongly impact the conduction mechanism in the channel layer of the TFT.

In this study, molybdenum doped indium oxide is sputtered onto ALD deposited HfO2 with or without pattering, and etched by RIE chlorine based processing. Nanoparticle formation is observed when photoresist is removed by oxygen plasma ashing. HfO2 etching in CF4/Ar plasma prior to resist stripping in oxygen plasma promotes the aggregation of nanoparticles into nanosized branched structures. Such nanostructuring is absent when oxygen plasma steps are replaced by chemical wet processing with acetone.

Finally, in order to understand the electronic transport effect of the nanoparticles on metal oxide thin film transistors, TFT have been fabricated and electrically characterized.

10105-27, Session 10

Identification of surface acoustic waves in ZnO materials by Brillouin light scattering for SAW device applications *(Invited Paper)*

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Transparent conducting oxides, such as zinc oxide (ZnO), are of high technological relevance for applications such as flat panel displays for smart phone, for contacts on thin film photo-voltaic, and Wight light emitting diode (LED). ZnO is also well-known as a piezoelectric material for use in surface acoustic wave (SAW) devices in delay lines, gas sensor, as gyroscope in smarts phones, oscillator in wireless communications and signal processing.

ZnO is characterized as having an axis [002] perpendicular to the surface plane. The plane formed between this axis and the direction of propagation confers the ability to excite a plurality of elastic modes of vibration in volume and surface via piezoelectric effect.

We modeled the surface propagation modes in ZnO, thanks to the elastic equations of propagation. The study was conducted on the ZnO bulk and thin layers. The study demonstrated the presence of the principal mode of Rayleigh and high speed modes, several Sezawa's modes. The theoretical study among other predicted the possibility of the excited guided longitudinal mode. The latter is characterized by a speed greater than 6000 m / s, one of acoustic surface wave velocity never calculated for the ZnO thin film.

In contrast, an experimental study was conducted by Brillouin light scattering characterization (BLS) to confirm the calculated vibration modes. This measurement technique is based on diffusion between a laser beam and the elastic wave.

The measurement technique shows promise for the detection of the elastic waves. It allows presenting as first the nature of the vibrations before proceeding to the implementation of the SAW device.

10105-28, Session 10

Do piezoelectric and piezomagnetic sensors help in simulation of stress propagation prior to seismic events and hence display preseismic signature?

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Pizeolecrtric and Pizeomagnetic materials like pbtio2,quartz, PbGatio2gallium titanate are quite susceptible to the im;lied stress and respond proportionately in direction and magnitude to the electric voltage. The intensity ,na

magnitude and direction depends on the configuration and dimension of the mnaterial configurated,For desirted voltage a demarcated coupling factor are designed to respond accordingly.similar way the pizeomagnetic substances are reponding Viz CoF2 and MnF2 to the applied mechanical stressinproportionate manner.objectives are targeted to capture the pizeomagnetic signals as confirmatory and Pizeoelectric signals induced due to stress applied as preseismic signature in the subsurface of crustal region.

Integrated circuit in the block dagram proposed can be worked out to reveal the mathematics and mechanics of the electrical and magnetic energy transformation from mechanical stress.Our findings are surrounding the EM theory of maxwell and farady laws of electrodynamics.Next wise configuration and setting up of the sensors of ceramic selected responds to the desired level. Mathematics and mechanics of Pizeolel;ctricoity approves the transformation of energy.Thus can help in manufacturing optoelectrnic device for preseismic signature.

10105-29, Session 11

The use of oxide template layers for the growth of (in)GaN-based devices *(Invited Paper)*

Abdallah Ougazzaden, Renaud Puybaret, Suresh Sundaram, Youssef El Gmili, Paul L. Voss, Georgia Tech-Lorraine (France); Jean Paul Salvestrini, Lab. Matériauy Optiques, Photonique et Systèmes (LMOPS) (France); David J. Rogers, Ferechteh H. Teherani, Vinod Eric Sandana, Philippe Bove, Nanovation (France); Ryan McClintock, Manijeh Razeghi, Northwestern Univ. (United States)

No Abstract Available

10105-30, Session 11

Magnetic properties of cobalt oxide nanoparticles

Hal Gokturk, Ecoken (United States)

Magnetic materials like gadolinium (Gd) and GdSiGe alloys which have Curie temperatures (Tc) close to room temperature are getting attention due to their potential applications in magnetic refrigeration [1]. In this research anti-ferromagnetic properties of nanoparticles of cobalt oxide (CoO) are investigated. Neel temperature (Tn) of CoO in bulk form is about 18°C, similar to the Tc of Gd.

The study has been carried out with quantum mechanical calculations using the DFT method with B3LYP functional and Pople type basis sets augmented with polarization functions. Atomic models consist of nanoparticles of various sizes which are carved out from the bulk crystal of CoO maintaining symmetry as much as possible.

Geometry of each nanoparticle is calculated in two ways to determine the state of the nanoparticle above and below Tn: (a) Non-magnetic geometry where spin densities of individual atoms are zero (T>>Tn). (b) Magnetic geometry where spin densities of individual atoms are non-zero (T<< Tn).

Results indicate that quantum mechanical energy of the magnetic nanoparticle is lower than that of the non-magnetic nanoparticle, as expected. The difference in energy, which corresponds to the magnetic phase transition energy, is 3.6 eV for the smallest particle of $(CoO)_4$. The energy difference becomes smaller with increasing size of the nanoparticle. For example at $(CoO)_9$ the energy difference is only 0.8 eV.

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10105-31, Session 11

Monolithic integration of metal-ferroelectric-semiconductor heterostructure using atomic layer deposition

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Integration of functional oxides with silicon and germanium enables the realization of novel electronics device designs and the improvement of device performance, without fundamentally altering semiconductor device physics and manufacturing processes. In particular, the wide variety of perovskite oxides and their ability to grow epitaxially on silicon and germanium allows the design of monolithically integrated semiconductor devices. Here, we demonstrate the fabrication of monolithically integrated metal-ferroelectric-semiconductor structures. $La_xSr_{1-x}TiO_3/BaTiO_3/SrTiO_3/Si$ (La:STO/BTO/STO/Si) and La:STO/BTO/Ge structures were fabricated using atomic layer deposition (ALD). The low processing temperature afforded by ALD prevents the formation of low-permittivity SiO_x or GeO_x interlayer, while using germanium semiconductor enables an ALD-only fabrication process. Aberration-corrected microscopy confirms the monolithic integration of the metal-ferroelectric-semiconductor structures, as well as the lack of amorphous oxide interlayer between semiconductor and ferroelectric layers. X-ray diffraction shows the tetragonal nature of BTO film, with its long axis pointing perpendicular to the surface plane, suggesting out-of-plane ferroelectric polarization. X-ray photoelectron spectroscopy and transport measurements reveal the role oxygen content plays in La:STO film conductivity, and additional process considerations need to be made to ensure La:STO conductivity in oxide-based heterostructures. The structures reported here demonstrated the feasibility of fabricating ferroelectric field effect devices that are monolithically integrated into silicon and/or germanium platforms.

10105-32, Session 11

Optical power diodes based on phase-transition materials

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Goldsmith, Univ. of Wisconsin-Madison (United States); Carsten Ronning, Friedrich-Schiller-Univ. Jena (Germany); Mikhail A. Kats, Univ. of Wisconsin-Madison (United States)

We present several designs and experimental implementations of optical power diodes – devices that are designed to be transparent from one direction, but opaque from the other, when illuminated by a beam with sufficient intensity. Optical power diodes can be used to protect optical devices that both detect and transmit light.

Our designs are based on phase-change material vanadium dioxide (VO2), which undergoes an insulator-to-metal transition (IMT) that can be triggered thermally or optically. Here, VO2 films serve as nonlinear elements that can be transformed from transparent to opaque by intense illumination. We build thin-film metallic structures on top of the VO2 films such that the optical absorption becomes asymmetric – light impinging from one direction is absorbed at a higher rate than from the other direction, triggering the transition, and turning the device opaque. This results in asymmetric transmission.

The designs are optimized with finite-difference time-domain (FDTD) simulations, using optical constants of VO2 extracted using ellipsometry, and are shown to be scalable across the near- and mid-infrared. Our initial experimental results using a simple design comprised of metal and VO2 films on sapphire, designed for an operating wavelength of 1.35µm, show a transmission asymmetry ratio of ~2, and experiments with superior designs are ongoing. Future work will include the use of defect-engineered VO2 to engineer the intensity threshold of optical power diodes.

10105-80, Session 11

Interfacial coupling and polarization of ABO3 heterostructures *(Invited Paper)*

Yimei Zhu, Brookhaven National Lab. (United States)

Interfaces with subtle difference in atomic and electronic structures in perovskite ABO3 heterostructures often yield intriguingly different properties, yet their exact roles remain elusive. In this presentation, we report an integrated study of unusual transport, magnetic, and structural properties of Pr0.67Sr0.33MnO3 films and La0.67Sr0.33MnO3 films of various thicknesses on SrTiO3 (STO) substrate. In particular, using atomically resolved imaging and electron energy-loss spectroscopy, we measure interface related local lattice distortion, BO6 octahedral rotation and cation-anion displacement induced polarization. In the very thin Pr0.67Sr0.33MnO3 film, an unexpected interface-induced ferromagnetic polaronic insulator phase was observed during the cubic-to-tetragonal phase transition of STO, due to the enhanced electron-phonon interaction and atomic disorder in the film. For the very thin La0.67Sr0.33MnO3 films we reveal a remarkably deep polarization in non-ferroelectric STO near the interface due to its build-in electric field. Combining the experimental results with first principles calculations, we propose that the observed deep polarization and field are originated from oxygen vacancies that extend beyond a dozen unit-cells from the interface, thus providing important evidence of the role of defects in the emergent interface properties of transition metal oxides.

10105-33, Session 12

Zinc nitride thin films: basic properties and applications *(Invited Paper)*

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Zinc nitride (Zn3N2) is a semimetal with a band gap energy of 1.23 eV, high mobilities (~100 cm2/V·s), high carrier densities (1018-1020 cm-3), and low resistivities (10-2-10-3 ?·cm) [1]. It has a black colour and it tends to form polycrystalline films when it is deposited by magnetron sputtering at low temperatures (T < 500 K) using reactive N2 plasma. Despite the reported fabrication of electronic devices from those films [2,3], Zn3N2 is still poorly developed due to the transformation into ZnO in normal ambient conditions [4]. The transformation starts at the top surface and propagates vertically up to reaching the interface with the substrate. As a result of the transformation, the material becomes insulating and transparent in appearance.

In this work, we will present our studies on the transformation of Zn3N2 into ZnO using scanning electron and atomic force microscopy (SEM, AFM), spectroscopic ellipsometry (SE), X-ray diffraction (XRD) and elastic recoil detection analysis with time-of-flight telescope (ERDA-TOF). Different ambient conditions has been tested to compare the transformation rates of Zn3N2 films and zinc oxynitride alloys. Passivation of the surface has been also studied using thin capping layers of ZnO. Those studies have allowed us to develop sensors on glass substrates and transparent flexible polycarbonates. Those sensors have been characterized optically and electrically during the transformation. The application of this technology to monitor air parameters and human perspiration properties will be discussed.

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10105-34, Session 12

Oxides and nitrides for applications in plasmonics *(Invited Paper)*

Urcan Guler, Jongbum Kim, Nathaniel Kinsey, Clayton T. DeVault, Aveek Dutta, Sajid Choudhuri, Alexander V. Kildishev, Vladimir M. Shalaev, Alexandra Boltasseva, Purdue Univ. (United States)

Transition metal nitrides (TMNs) and transparent conducting oxides (TCOs) exhibit plasmonic behavior in the visible and near-infrared (NIR) ranges while providing unique solutions to some material-related, application specific problems.

TCOs are wide bandgap semiconductors with a carrier concentration of around 10^21 cm^-3 which makes them low-loss plasmonic materials in the NIR. TCOs are thus promising candidates for transformation optics and have been used in metasurfaces for beam steering, phase-front engineering as well as in chemical sensing and active optical components for modulators. Our work on TCOs is based on Aluminium and Gallium doped Zinc Oxides (AZO and GZO) which are grown by pulsed laser deposition. The plasma frequency in these materials can be tuned in the NIR (between 1.2-2?m in wavelength) by varying the O2 partial pressure while deposition, by changing the deposition temperature or by post-deposition annealing.

TMNs exhibit plasmon resonance in the visible and NIR regions. Their refractory properties enable plasmonic components capable of operating under harsh environmental conditions such as extremely high temperatures or aggressive chemistry. Single crystalline titanium nitride (TiN) and zirconium nitride (ZrN) nanostructures are utilized as plasmonic components in metamaterials, metasurfaces, near-field transducers, waveguides, photo-thermal therapy and photocatalysis.

10105-35, Session 12

Electronic structure and properties of transparent conducting oxide semiconductors *(Invited Paper)*

Chris F. McConville, The Univ. of Warwick (United Kingdom)

Oxide semiconductors have become of great technological interest and importance in recent years with opportunities to improve existing materials and device applications. This is particularly true for a sub-group of materials that display both optical transparency and high electrical conductivity, so-called transparent conducting oxides (TCO's). The fact that some of these materials, such indium tin oxide have been around for many years and seen significant industrial use as transparent conductors in a relatively low quality form, has perhaps contributed to the belated recognition of using these materials as semiconductors in their own right. Here, examples of the surface and bulk electronic properties of epitaxially grown oxide semiconductors (CdO, In2O3, and ZnO) will be discussed along with the effects of modifying these surfaces by controlled adsorption. The valence band density of states and the surface electronic properties of these TCO's have been studied using high-resolution angle-resolved photoemission (ARPES), while core-level photoemission spectroscopy with hard x-rays (HAXPES) is compared with theoretical DFT band structure calculations. A common property of these oxide semiconductors is the presence of an electron accumulation layer at the surface. While this is similar to that found at the surfaces of materials such as InN and In-rich InGaN, it is in marked contrast to the electron depletion typically observed at the surfaces of conventional III-V and II-VI semiconductor materials. More unusual still is the quantized nature of this surface 2D electron gas. The origins of these phenomena will be discussed in terms of the band structure and intrinsic properties of the materials.

10105-36, Session 12

Intersubband spectroscopy of ZnO/ZnMgO quantum wells grown on m-plane ZnO substrates for quantum cascade device applications

Patrick Quach, Arnaud Jollivet, Nathalie Isac, Adel Bousseksou, Frédéric Ariel, Maria Tchernycheva, François H. Julien, Univ. Paris-Sud 11 (France); Miguel Montes Bajo, Julen Tamayo-Arriola, Adrián Hierro, Univ. Politécnica de Madrid (Spain); Nolwenn Le Biavan, Maxime Hugues, Jean-Michel Chauveau, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France)

Quantum cascade (QC) lasers opens new prospects for powerful sources operating at THz frequencies. Up to now the best THz QC lasers are based on intersubband emission in GaAs/AlGaAs quantum well (QW) heterostructures. The maximum operating temperature is 200 K, which is too low for wide-spread applications. This is due to the rather low LO-phonon energy (36 meV) of GaAs-based materials. Indeed, thermal activation allows non-radiative path through electron-phonon interaction which destroys the population inversion. Wide band gap materials such as ZnO have been predicted to provide much higher operating temperatures because of the high value of their LO-phonon energy. However, despite some observations of intersubband absorption in c-plane ZnO/ZnMgO quantum wells, little is known on the fundamental parameters such as the conduction band offset in such heterostructures. In addition the internal field inherent to c-plane grown heterostuctures is an handicap for the design of QC lasers and detectors.

In this talk, we will review a systematic investigation of ZnO/ZnMgO QW heterostructures with various Mg content and QW thicknesses grown by plasma molecular beam epitaxy on low-defect m-plane ZnO substrates. We will show that most samples exhibit TM-polarized intersubband absorption at room temperature linked either to bound-to-quasi bound inter-miniband absorption or to bound-to bound intersubband absorption depending on the Mg content of the barrier material. This systematic study allows for the first time to estimate the conduction band offset of ZnO/ZnMgO heterostructures, opening prospects for the design of QC devices operating at THz frequencies.

10105-37, Session 13

Effect of ZnO surface defects on efficiency and stability of ZnO-based perovskite solar cells *(Invited Paper)*

Fangzhou Liu, Man Kwong Wong, Ho Won Tam, Aleksandra B. Djuri?i?, The Univ. of Hong Kong (Hong Kong, China); Alan Man Ching Ng, South Univ. of Science and Technology of China (China); Wai Kin Chan, The Univ. of Hong Kong (Hong Kong, China)

Organic-inorganic hybrid perovskite based solar cells have demonstrated great potentials as the next generation photovoltaic devices in the recent years with the highest energy converting efficiency exceeded 22% in 2016.1 In addition to the remarkable progress achieved in devices with TiO2 as the electron transporting material, ZnO-based devices have drawn increasing research interest due to its comparable energy levels to TiO2, relatively high electron mobility, as well as its feasibility to be processed at low temperatures that allows fabrications of flexible devices.2 Nevertheless, ZnO-based perovskite devices usually exhibit severe stability drawbacks due to the reactions at ZnO/perovskite interface which is related to the surface defects of ZnO. 3-4 Attempts have been made to improve the stability of ZnO based devices by inserting an interlayer such as Al2O3 3 or Al-doped ZnO (AZO)4 in between ZnO and perovskite absorbers to inhibit degradation of perovskites. However, the effect of directly manipulating the surface defects of ZnO is seldom reported.

This study focuses on the influence of defects of the ZnO compact layers on the efficiency and stability of the perovskite solar cells. ZnO compact layers were prepared by solution process as well as vapor deposition, and subjected to various surface treatments including plasma treatment and UV surface treatments. Modifications of surface defects of ZnO resulted from different treatments were characterized by photoluminescence (PL) and X-ray photoelectron spectroscopy (XPS). Planar structured perovskite solar cells were fabricated based on ZnO compact layers with different defect contents, and the influence on the device performance and stability were investigated in detail.

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10105-38, Session 13

Nanostructured photovoltaic devices: controlled growth and properties of ZnO nanowires *(Invited Paper)*

Silvija Gradecak, Massachusetts Institute of Technology (United States)

No Abstract Available

10105-39, Session 13

Low-temperature solution-processed delafossite thin films as hole transport layer for organic and perovskite photovoltaic devices *(Invited Paper)*

Jian Wang, Univ. of Dallas (United States); Wiley Dunlap-Shohl, Duke Univ. (United States); Daniel Wang, Trey B. Daunis, The Univ. of Texas at Dallas (United States); David B. Mitzi, Duke Univ. (United States); Julia W. P. Hsu, The Univ. of Texas at Dallas (United States)

A metal oxide hole transport layer (HTL) greatly improves the performance and stability of organic photovoltaic (OPV) and halide perovskite photovoltaic devices. Currently, much research attention has been put onto developing p-type HTLs, most notably NiOx. Here, we report the use of Cu(1+)-based delafossite compound, Cu(1+)M(3+)O2 (M= Al, Ga, Cr, etc.), as p-type HTL for OPV and perovskite photovoltaic devices. As a p-type transparent conducting oxide (p-TCO) material, CuMO2 has been previously applied as photocathode in p-type dye sensitized solar cells and water splitting. Compared with the commonly used NiOx, delafossite compounds usually have deeper valence band edge, higher hole mobility, and better optical transparency, making these oxides promising p-type HTL candidates for OPV and perovskite photovoltaic devices. However, previous reported CuMO2 films are either vacuum deposited or processed under high temperature (700 ~ 1100 °C), making them incompatible for depositing on commonly used ITO or FTO substrates for these PV devices. Here we demonstrate two low-temperature preparation methods of CuMO2 thin films for HTLs in OPV & perovskite photovoltaic devices. In the 1st route, we would review a microwave-assisted hydrothermal synthesis for delafossite nanoparticle suspensions. Room temperature deposited HTLs from these suspensions produce efficient OPV devices. In the 2nd route, we report our newly developed combustion-reaction based sol-gel approach to deposit thin films at temperature as low as 170 °C. These delafossite films are smooth and highly transparent, which produce efficient OPV and perovskite photovoltaic devices. In the presentation, details of film preparation, optoelectrical property characterization, and PV device characteristics will be discussed.

10105-40, Session 13

ZnO growth for heterostructure solar cell *(Invited Paper)*

Abasifreke U. Ebong, The Univ. of North Carolina at Charlotte (United States)

Zinc oxide (ZnO) is one of the multipurpose materials with myriads applications both as thin film and nanostructures. ZnO can be used for solar cell window layer, gas sensor, light emitting diode (LED) and substrate to grow Gallium Nitride (GaN). It is low-cost and abundant with a bandgap of 3.4 eV that makes it transparent to the solar spectrum from 300 -1200 nm. Intrinsically, ZnO is an n-type material due to the number of defects introduced during the growth, irrespective of growth method. These defects are commonly believed to be Zn interstitial and oxygen vacancy. To grow p-type ZnO or achieve p-conductivity is very challenging, that is why the formation of pn junction with an n-type silicon is still under developing. There are numerous methods for growing ZnO thin film, from chemical solution to Molecular Beam Epitaxy (MBE), sputtering, Metal-Organic Chemical Vapour Deposition (MOCVD), atomic layer deposition (ALD), pulse laser deposition (PLD) etc. This paper will discuss the methods of growth of ZnO heterostructure solar cell. It will compare and contrast the electrical characteristics of heterostructure solar cell with the growth method.

10105-41, Session 14

Ultra-wide broadband dielectric mirrors for solar collector applications

Markus Fredell, Kirk Winchester, Gregg W. Jarvis, Thomas D. Rahmlow, Robert L. Johnson Jr., Omega Optical, Inc. (United States); Mark Keevers, The Univ. of South Wales (Australia)

High efficiency solar conversion requires conversion across a broad spectrum of wavelengths from the ultra-violet into the infrared. Solar collector mirrors must provide high reflection across this spectral band without degrading over time. This work presents the results of a set of high-performance 200 mm parabolic mirrors coated with an ultra-wide broadband dielectric coating. The mirror was developed to demonstrate high efficiency broadband solar collection and power conversion. Mirror reflection was measured within the limits of NIST capabilities, and averaged over 99.65% from 400 to 1800 nm with a wide acceptance angle. Plasma-assisted reactive magnetron sputtering was used to produce these high density and environmentally stable films. These hard oxide films can be repeatedly cleaned in the field. Salt spray, humidity and wide angle performance results are presented.

10105-42, Session 14

ZnO for solar cell applications *(Invited Paper)*

Ian T. Ferguson, Missouri Univ. of Science and Technology (United States)

No Abstract Available

10105-69, Session 14

Multifunctional materials for solar technologies *(Invited Paper)*

Federico Rosei, Institut National de la Recherche Scientifique (Canada)

As the age of fossil fuels is coming to an end, now more than ever there is the need for more efficient and sustainable renewable energy technologies. Nanostructured materials synthesized via the bottom–up approach present an opportunity for future generation low cost manufacturing of devices [1]. We demonstrate various strategies to control nanostructure assembly, to design and synthesize functional materials that will help address the energy challenge. We study, in particular, multifunctional materials, namely materials that exhibit more than one functionality, and structure/property relationships in such systems, including for example: (i) control of size and luminescence properties of semiconductor nanostructures, synthesized by reactive laser ablation [2]; (ii) we devised new strategies for synthesizing multifunctional nanoscale materials to be used for applications electronics and photovoltaics [3-26].

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10105-43, Session 15

Epitaxial structures for solar blind UV photodetectors *(Invited Paper)*

Andrei V. Osinsky, Agnitron Technology, Inc. (United States)

No Abstract Available

10105-44, Session 15

High rejection ratio solar-blind wurtzite MgZnO photodetectors

Mykyta Toporkov, Partha Mukhopadhyay, Sara Bakhshi, Valeria Beletsky, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Fikadu Alema, Andrei V. Osinsky, Agnitron Technology, Inc. (United States)

MgZnO based planar Metal-Semiconductor-Metal (MSM) solar-blind photodetectors with high rejection ratio were fabricated by utilizing solar-blind buffer layers such as wurtzite MgO (w-MgO) and AlN. High quality single crystal wurtzite MgyZn1-yO thin films were grown by plasma-assisted molecular beam epitaxy on w-MgO/sapphire and AlN/sapphire templates with Mg content above y=0.45. Pt metal was used to form Schottky barrier contacts in interdigitated electrode geometry. Additionally, we report on vertical Schottky barrier solar-blind photodetectors grown on single crystal Pt films. The top Pt electrode is formed with ~5nm semitransparent Pt layer with 50% transmittance in the solar-blind area. Resulting devices showed peak responsivity at wavelength of ~280nm. A specific focus of this work is to fabricate high rejection ratio solar-blind photodetectors and identify ways to grow high quality wurtzite MgZnO thin films on solar-blind templates and eliminate undesirable photo response from non-solar blind buffer layers (such as ZnO).

10105-45, Session 15

Ultra-wide bandgap beta-Ga2O3 for deep-UV solar blind photodetectors

Subrina Rafique, Lu Han, Hongping Zhao, Case Western Reserve Univ. (United States)

Deep-ultraviolet (DUV) photodetectors based on wide bandgap (WB) semiconductor materials have attracted strong interest because of their broad applications in military surveillance, fire detection and ozone hole monitoring. Monoclinic ?-Ga2O3 with ultra-wide bandgap of ~4.9 eV is a promising candidate for such application because of its high optical transparency in UV and visible wavelength region, and excellent thermal and chemical stability at elevated temperatures. Synthesis of high quality?-Ga2O3 thin films is still at its early stage and knowledge on the origins of defects in this material is lacking. The conventional epitaxy methods used to grow ?-Ga2O3 thin films such as molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD) still face great challenges such as limited growth rate and relatively high defects levels. In this work, we present the growth of ?-Ga2O3 thin films on c-plane (0001) sapphire substrate by our recently developed low pressure chemical vapor deposition (LPCVD) method. The ?-Ga2O3 thin films synthesized using high purity metallic gallium and oxygen as the source precursors and argon as carrier gas show controllable N-type doping and high carrier mobility. Metal-semiconductor-metal (MSM) photodetectors (PDs) were fabricated on the as-grown ?-Ga2O3 thin films. Au/Ti thin films deposited by e-beam evaporation served as the contact metals. Optimization of the thin film growth conditions and the effects of thermal annealing on the performance of the PDs were investigated. The responsivity of devices under 250 nm UV light irradiation as well as dark light will be characterized and compared.

10105-46, Session 16

Optical properties of alpha-, beta-, and epsilon-Ga2O3

Axel Hoffmann, Nadja Jankowski, Christian Nenstiel, Gordon Callsen, Markus R. Wagner, Technische Univ. Berlin (Germany); Zbigniew Galazka, Klaus Irmscher, Martin Albrecht, Leibniz-Institut für Kristallzüchtung (Germany); Martin Eickhoff, Justus-Liebig-Univ. Giessen (Germany)

In recent years, the optically anisotropic wide band gap semiconductor Ga2O3 has attracted much attention triggered by its potential for applications such as photo detectors, gas sensors, field effect transistors, and UV transparent electrodes. However, the determination of its optical and electronic properties is more challenging compared to other wide bandgap semiconductors like ZnO or GaN due to the pronounced crystal anisotropy, the existence of five different structural modifications, and the common absence of band edge related luminescence bands. Consequently, many of the usually well-known fundamental properties of semiconductors such as the optical band gap, exciton binding energies, valence band fine structure, and vibrational lattice modes of the different modifications of Ga2O3 are not precisely measured or are subject of controversy.

In this contribution, we present a comprehensive study of the optical and vibrational properties of Ga2O3 in the alpha-, beta-, and epsilon-modification. Polychromatic photoluminescence excitation measurements (PLE) are performed to investigate the near band edge excitation channels for the commonly observed self-trapped exciton luminescence. Polarized PLE measurements clearly show the splitting of px and pz states as well as the variation of the optical band gap between the different modification. Temperature dependent polarized PLE measurements reveal an increase of the px-pz splitting with increasing temperature which is discussed considering the electronic band structure of Ga2O3. In addition, we performed polarized and angular dependent micro-Raman measurements in order to derive the anisotropic Raman tensor elements. The results are discussed with respect to recently published theoretical calculations and shed new light on the optical and vibrational properties of Ga2O3 in different modifications.

10105-47, Session 16

Pulsed laser deposition of B-Ga2O3

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Ultra-wide bandgap materials such as beta gallium-oxide (?-Ga?O?) are attracting substantial interest because of their electrical and optical properties and their potential for UV light emitting diodes and lasers. ?-Ga?O? is highly transparent in a broad band of the electro-magnetic spectrum because of its wide bandgap of 4.9 eV.

In this work, ?-Ga?O? was grown by pulsed laser deposition on sapphire and magnesium oxide substrates at substrate temperatures ranging from 300 to 650 °C. The samples were characterized with XRD and Raman backscattering measurements. The absorption coefficients were obtained from UV-VIS measurements. With increasing substrate temperature the

deposition rate, r, decreases to about 0.5 and 0.8 Å/s on MgO and sapphire substrates, respectively. This decrease can be recovered by increasing the oxygen partial pressusre to 10?? mbar, which results in an increase of r to about 2.5 Å/s . The substrate, the oxygen partial preassure, and the growth temperature have a significant influence on the optical bandgap of ?-Ga?O?. For ?-Ga?O? on sapphire the bandgap increases from about 3.8 eV at 300 °C to 4.9 eV at 650 °C. On MgO substrates the bandgap increases for the same temperature change from 4.6 to 4.82 eV. On the other hand, for a fixed deposition temperature the bandgap decreases with increasing oxygen partial pressure. The substrate temperature, oxygen partial pressure and the choice of substrate also influence the position of the lattice phonons. An increase of the growth temperature results in a shift of the phonon modes to higher frequencies while an increase of the oxygen partial pressure for a fixed deposition temperature results in a decrease of the phonon frequencies. The experimental results will be discussed in terms of crystal quality and lattice strain.

10105-48, Session 16

Investigations on the substrate dependence of the properties in nominally-undoped beta-Ga2O3 thin films grown by PLD

David J. Rogers, Ferechteh H. Teherani, Vinod Eric Sandana, Philippe Bove, Nanovation (France); Ekaterine Chikoidze, François Jomard, Michael Neumann, Yves Dumont, Univ. de Versailles Saint-Quentin-en Yvelines (France); Thuan Huynh, Laurent Lee Cheong Lem, Matthew R. Phillips, Cuong Ton-That, Univ. of Technology, Sydney (Australia); Ryan McClintock, Manijeh Razeghi, Northwestern Univ. (United States)

No Abstract Available

10105-52, Session 17

Oscillation valence electron model of superconducting cuprates

Nadezhda P. Netesova, M.V. Lomonosov Moscow SU (Russian Federation)

For the first time, Neel, the winner of the Nobel Prize, has applied sublattice theory to explain the magnetism of multicomponent systems. Within the bioscillator electron model [1] a superconducting phase transition in the crystal AB is accomplished by break valence ties, the formation of paired electrons or molecule sublattices of A2 and B2: 2AB=A2+B2. Energy ? balance equations are 2?2[AB]≤?2[A2]+?2[B2], ?2[AB]≤?2[A2], ?2[AB]≤?2[B2].

The mechanism of the superconducting phase transition in the yttrium-barium YBaCuO or other cuprates under poly oscillator electron model is examined. In the first stage there are formed yttrium, barium (or other elements) and copper oxides, in the second stage the oxides are dissociated. The molecules are formed, provided that the atom association energy is more gap energy of valence bonds in oxides. Calculations of quadratic energies for the oxides and cuprates to room temperature and 90K are performed.

YBa2Cu3O6.5 = 0.5Y2O3+2BaO+3CuO = (0.5Y2+0.75O2) + (Ba2+O2) + (1.5Cu2+1.5O2).

At 293? ?2 [O2] = 0.4761, ?2 [YBa2Cu3O6.5] = 406.4256,

406.4256 > 62.2728+1.5?0.4761, 406.4256 > 45.6976+2?0.4761, 406.4256 > 349.3014+3?0.4761.

At 90K ?2 [O2] = 354.9456, ?2 [YBa2Cu3O6.5] = 406.4256,

406.4256 > (62.2728+266.209) = 328.482, 406.4256 > (45.6976 + 354.9456) = 400.6432,

406.4256 < (349.3014 + 532.4184) = 881.7198.

To superconducting phase transition has been occurred, the quadratic energy must be greater than the criterion. The cuprate with a stoichiometric composition is not a superconductor according to experimental data. The balance equations at 90K are consistent with the experimental data 406.4256?2 ? (328.482+400.6432) = 83.726 eV2. The total quadratic energy required for education Y2 and Ba2 molecules is equal to 812.8512 eV2.

Cuprates with the introduction of additional oxygen typeYBa2Cu3O6.5 + 0.5 are superconductors.

The energies of the valence bonds are reduced the introduction of oxygen above stoichiometric values by expanding crystal lattice.

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10105-71, Session 17

Microwave nonlinear response of oxide superconducting films in the Berezinskii-Kosterlitz-Thouless state *(Invited Paper)*

Sergey Vitkalov, The City College of New York (United States) and Physics Department at Columbia University (United States); Scott Dietrich, Physics Department at Columbia University (United States); William Mayer, The City College of New York (United States); A. Sergeev, US Army Research Laboratory (United States); Anthony T. Bollinger, Ivan Bozovic, Brookhaven National Lab. (United States)

The Berezinskii-Kosterlitz-Thouless (BKT) phase transition originates from long range attraction between vortex and anti-vortex leading to pairing of these excitations below critical temperature Tc. The effects of microwave radiation on transport properties of atomically thin superconducting La 2?xSrxCuO4 films were studied in the 0.1–13 GHz frequency range near BKT transition above Tc. The microwave nonlinear response is found decreasing by several orders of magnitude within a few GHz of a cutoff frequency f ≈ 2 GHz. The results indicate that two-dimensional superconductivity is resilient against high-frequency radiation, which is related to strong suppression of the dissociation of the vortex-antivortex pairs in 2D superconducting condensates oscillating at high frequencies.

10105-73, Session 17

Spin-orbit coupled superconductivity at the interface of LaAlO3/SrTiO3 *(Invited Paper)*

Chi?Sheng Li, Akhilesh Kr. Singh, Ming-Yuan Song, Wei-Li Lee, Institute of Physics, Academia Sinica (Taiwan)

By using oxide MBE technique, we have grown few monolayers of epitaxial LaAlO3 (LAO) on TiO2 terminated SrTiO3 (STO) substrates, which shows an interface superconductivity below about 0.3 K. Scanning tunneling electron microscope images revealed a sharp atomic interface between LAO and STO in our LAO/STO samples. By fabricating a back gate electrode via the STO substrate, the superconductor?insulator transition was observed by applying gate voltages on a macroscopic size of the two?dimensional electron liquid (2DEL) at the interface of LAO/STO. From the superconducting critical field anisotropy measurements, a sizable spin?orbit coupling (SOC) is likely to present in the superconducting phase, where the upper limit of the SOC strength can be largely tuned by gate voltages. In addition, magneto?transport anomaly was found when depleting the electron density and thus driving the 2DEL into insulating phase, suggesting an inhomogeneous density distribution and also a possible multi?band conduction in the 2DEL.

10105-76, Session 17

Multiphonon contribution to the polaron formation in cuprates with strong electron correlations and strong electron-phonon interaction *(Invited Paper)*

Sergei G. Ovchinnikov, Ilya Makarov, Petr Kozlov, Kirensky Institute of Physics (Russian Federation)

The generalized tight binding (GTB) method to calculate the electronic structure of strongly correlated electrons in cuprates is modified to incorporate also strong electron-phonon interaction. By exact diagonalization of the p-d- Holstain model Hamiltonian for a separate CuO6 unit cell we find the multelectron and multiphonon local eigenstates that are used to construct a set of local Hubbard operators. Then we treat the intercell electron hopping t by the perturbation approach over small ratio t/U, where U is the charge transfer excitation energy. Without electron-phonon interaction we obtain the band of spin polaron and a set of local multiphonon Franck-Condon excitations. The electron-phonon interaction results in the hybridization of spin polaron and Franck-Condon excitations that forms the polaronic band structurewith strong temperature dependence. The peak of a spectral function at the top of the valence band has large width typical to the ARPES data and is determined by a large number of the multiphonon excitations.

10105-82, Session 17

Why only hole conductors can be superconductors *(Invited Paper)*

J. E. Hirsch, Univ. of California, San Diego (United States)

The conventional theory of superconductivity says that charge carriers in a metal that becomes superconducting can be either electrons or holes. I argue that this is incorrect, for the following reason. All superconductors exhibit the Meissner effect, which implies that the superconductor-normal phase transition in the presence of a magnetic field is reversible. In the superconducting state there is a supercurrent, in the normal state there is no current. The supercurrent carries mechanical momentum, while there is no mechanical momentum in the electronic normal state. I will argue that in order to conserve mechanical momentum in the superconductor to normal transition in the presence of a magnetic field it is necessary that the normal state charge carriers are holes [1,2}. I will also review the empirical evidence in favor of the hypothesis that all superconductors are hole superconductors and. discuss the implications of this for the search for higher Tc superconductors.

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10105-54, Session PWed

High performance flexible acetylene sensor using piezoelectric-plasmonic effects based on Ag nanoparticles decorated on ZnO nanorods

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In this study, piezoelectric and plasmonic effects on flexible acetylene (C2H2) sensor based on silver (Ag)-coated zinc-oxide (ZnO) nanorods were realized. Using visible light illumination, the sensing properties can be modulated and the power consumption can be reduced significantly. Upon exposure to 1000 ppm C2H2 under 8.36 mWcm-2 light illumination, the power consumption of the sensor noticeably reduced from 3.48 W (in dark) to 1.64 W. A large number of light induced chemisorbed oxygen ions were generated in the Ag-coated ZnO nanorods (NRs) forest due to the strong coupling effect between the surface plasmon Ag nanoparticles and the ZnO NRs. This resulted in increased surface charge densities, which facilitated the sensor to react with the C2H2 molecules at lower operating temperature, and hence reduce the power requirement. Moreover, the sensor exhibited reliable detection of C2H2 gas within the concentration of 3-1000 ppm including a maximum sensor response of 26.16, response-recovery time of 66/68 sec, excellent mechanical stability of a bending angle up to 90o, and 104 cycles of repeated deformation processes. These results might facilitate research in developing a low power C2H2 sensor and will open up new approaches for future light modulated gas sensors.

10105-55, Session PWed

UV radiation and CH4 gas detection with a single ZnO:Pd nanowire

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Abstract

Semiconducting oxide nanowires (NWs) have demonstrated exceptional and unique properties in comparison with bulk materials and have been used as building blocks for nanoscale electronic and optoelectronic devices, especially in the bottom-up technologies. However, new impact has been introduced with devices based on a single nanowire. Due to very high surface-to-volume ratio of a single nanowire the surface phenomena can greatly affect the electrical properties, which can be transduced in an electrical signal. In this context, a gas sensing application is the prominent example for efficient use of semiconducting oxides NWs sensing properties [1-3]. In this work the improved UV sensing properties of a single ZnO:Pd NW compared to pristine ZnO NW grown by electrochemical deposition is reported. Fabricated nanosensors demonstrate higher responsivity and internal photoconductive gain. The response and recovery times are greatly improved. The main advantages of such devices are extra-low power consumption and miniature size which facilitate their integration into portable devices and nanodevices.

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10105-56, Session PWed

Solution-deposited Al2O3 dielectric towards fully-patterned thin film transistors on shape memory polymer

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Transparent and flexible thin film transistors (TFTs) have potential applications in growing areas such as displays, radio frequency ID tags, and biomedical devices. Shape memory polymer (SMP) substrates with improved thermal mechanical response can ease device processing, and add control to the product shape and modulus. Until date, TFTs developed on SMP substrates have been limited to costly vacuum deposition methods. While TFTs processed through more economical solution-based techniques achieve device performance close to their vacuum-processed counterparts, they have not yet been demonstrated on SMP substrates due to required high calcination temperatures (> 500 °C). To take full advantages of the SMP substrate and to reduce the manufacturing cost, low temperature (< 250 °C) solution-based processing is highly desirable. Here we report the photolithographic fabrication of solution-processed metal oxide TFTs on an SMP substrate. Using a UV-activated solution combustion process, transparent indium oxide (In2O3) thin films are deposited and patterned at low temperature (70 - 100 °C). Device performance as a function of dielectric material (HfO2 vs. SiN) and annealing temperature (200-350 °C) will be compared and discussed. To enable low power CMOS logic, we further extend this process to the fabrication of TFTs with p-type oxide-based semiconductors. In the presentation, detailed device processing and characteristics will be provided.

10105-57, Session PWed

Ultrafast optical reversible Feynman-double logic gate using lithium niobate based Mach Zehnder interferometers

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In this ultra fast computing era power optimization is a major technological challenge that requires new computing paradigms. Conservative and reversible logic opens up the possibility of ultralow power computing. In this paper, basic reversible logic gate (double Feynman gate) using the lithium niobate based mach-zehnder interferometer is proposed. The results are verified using beam propagation method and MATLAB simulations.

10105-58, Session PWed

Improvement in grain size and crystallinity of sputtered ZnO thin film with optimized annealing ambient

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ZnO is gaining substantial interest day by day because of its wide bandgap (3.4 eV) and large exciton binding energy (60 meV) due to which lasing emission is possible from ZnO based materials even above room temperature.. Here we are reporting the influence of growth temperature and annealing ambient on photoluminescence properties, crystalline size and surface morphology of ZnO thin films deposited on Si substrates at 200˚C by RF sputtering. Achieved thickness is 198 nm as confirmed by Profilometer. Grown samples were further rapid thermal annealed at 800?C in Ar, N2, O2, and in vacuum ambient. The as-grown sample did not exhibit any near band edge emission peak due to presence of deep level defects. Low temperature (18 K) photoluminescence spectra exhibited strong emission peak around 3.32 eV when the as-grown sample was annealed at 800˚ C in oxygen ambient which indicates defects state passivation. A lowest full width half maximum (FWHM) of 73.85meV was achieved for sample annealed in O2 ambient .Sample annealed in vacuum showed peak with highest intensity at 3.25eV, which corresponds to donor-bound-acceptor (DAP). High resolution X-ray diffraction measurement exhibited a dominant <002> peak. Atomic Force Microscopy also revealed surface roughness of 7.72nm for sample annealed in O2 ambient. SPM Physics, IIT Bombay, DST, India are acknowledged.

10105-59, Session PWed

Small-subthreshold-swing ambipolar ZnO-multi layer graphene hybrid thin film transistors

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ZnO/graphene hybrid two dimensional thin film transistors (TFTs) is investigated for ZnO-based TFTs with a high on-off ratio and extremely high carrier mobility. We fabricated ZnO/multi-layer graphene (MLG) hybrid thin film transistors through a facile method by combining a sol-gel method for the ZnO film and transfer method for the MLG. The ZnO/MLG hybrid TFTs exhibited ambipolar behavior, an outstanding electron (hole) mobility of 828 (948) cm2/V?s, a high on-off ratio of 104 (104), and a small subthreshold swing of 15 (14) mV/decade. These ambipolar behaviors of the ZnO/MLG hybrid TFT can be attributed to the superimposed density of states associated with states in the ZnO bandgap and the linear dispersion of graphene. The small subthreshold swing value (14 mV/decade) is remarkably smaller than that of the graphene-based TFTs and ZnO/single layer graphene (SLG) hybrid TFTs (~ 10V/decade). The high mobility and the small subthreshold swing of the ZnO/MLG hybrid TFT are attributed to that the MLG decreases side effects of oxidation such as band gap opening due to the interaction between ZnO and graphene interface. The subthreshold swing is one of key parameters in evaluating the power consumption and operation speed of the TFTs. These results provide potential applications in the fabrication of TFTs with the low power consumption and high resolution for next generation flexible and large-area displays.

10105-60, Session PWed

Cycling performance of Mn2O3 porous nanocubes and hollow spheres for lithium-ion batteries

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In recent years, lithium ion batteries (LIBs) have attracted lots of interest since they are widely used in various areas. Researchers are looking for high-performance electrode materials with the capability of storing and delivering energy efficiently [1–4]. Mn2O3 has become popular owing to its potential advantages, such as high theoretical capacity (1018 mA h g?1), low operating voltage (the average discharge voltage is 0.5 V and charge voltage is 1.2 V), significant thermal stability and low cost [5–7].

Among different possible morphologies of Mn2O3, porous structures with high surface area and hollow structures which allow buffering of

volume changes are important for battery applications. In this work, we have explored the Li storage capability of Mn2O3 nanocubes with porous structure (MNC) [8] and Mn2O3 hollow spheres (MHS) [9].

Both morphologies were synthesized by a simple solvothermal process, followed by annealing. The morphology and properties were characterized by scanning electron microscope (SEM), transmission electron microscopy (TEM) and X-ray diffraction (XRD). The galvanostatic performance was measured by a Land battery test system (LAND-CT2001A) between 3.0 V and 0.01 V. Electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (C-V) measurements were both carried out using a BioLogic VMP3 electrochemical workstation. In addition, SEM and TEM images of electrodes before and after cycling were taken to study the reactions during charging and discharging process. We discuss the effect of crystallinity and morphology on the cycling and rate performance of Mn2O3-based electrodes in LIBs. The cycling performance and its relationship with material morphology will be discussed in detail.

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10105-61, Session PWed

Enhancement of photoluminescence in RF sputtered ZnMgO thin films by optimizing annealing temperature

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ZnMgO is a promising material for the future in the area of the optoelectronic devices due to the flexibility of changing bandgap. The impact of thermal annealing on ZnMgO thin films grown by RF sputtering on intrinsic Si substrate by RF sputtering at constant temperature 400˚C. During deposition gas flow 80% Argon and 20% oxygen was used. The samples were rapid thermal annealed at 900˚C (20 sec) and 950˚C for 20 and 30 sec to yield samples A, B and C, respectively. Low temperature photoluminescence (PL) measurements show presence of violet emission around 3.1 eV in as-grown sample due to the presence of zinc interstitial defects. Near-band-edge emission was found at around 3.65 eV for sample A. However, for sample B this peak was red-shifted and found around 3.63 eV but with much higher intensity. Further increase on annealing time (30 sec) sample was further red-shifted (sample C). On comparing with sample A, sample B showed 3 times enhancement in PL intensity and 30 times enhancement compared to as grown sample. X-ray diffraction measurements confirmed the growth of highly c-axis oriented <002> ZnMgO thin films for all samples. Uniform lattice constant (a= 0.29 and c= 0.51 nm) was achieved for all annealed samples. The <002> peak for all annealed samples shows higher intensity in comparison with the as-grown. A slight shift in the peak was observed which is due to presence of strain. For sample B surface roughness were measured 6.34nm. SPM Physics, IIT Bombay and DST, India are acknowledged.

10105-62, Session PWed

Plasma treatment for efficiency improvement of dye-sensitized solar cells using TCO-less substrate

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In commercial dye-sensitized solar cells (DSSCs), further reducing manufacturing cost and increasing solar cell efficiency is necessary. Transparent conducting oxide (TCO) glasses are estimated at ~ 60 % of the total fabrication cost of DSSCs. The cost ratio of TCO glass increases as the manufacturing process becomes more automated. The reduction of TCO glass cost, or structures without TCO glass, must be studied for financially feasible commercial DSSCs.

Some researchers have reported that TCO glass can be replaced with Ti-metal plates. Korron et al. reported on the TCO-free DSSCs with Ti-electrode, and showed an solar conversion efficiency of 3.6 %. TCO-free DSSCs have lower solar conversion efficiency than commercial fluorine-doped tin oxide (FTO)-substrate-based DSSCs. In order to improve the efficiency of Ti-electrode-based DSSCs, Kashiwa et al. reported on the effects of varying the thickness and porosity of the Ti-electrode, improved about 13.6 %. Therefore, the optimization of Ti characteristics is necessary for improving the solar conversion efficiency of Ti-electrode-based DSSCs. The surface roughness of Ti-electrodes must be increased to increase the adherence ability of TiO2 on the Ti-electrode, which is important for high solar conversion efficiency.

Recently, plasma treatments have been applied to TiO2 thin films to enhance DSSCs performance. Plasma treatment can be used to control a surface's degree of hydrophilicity or hydrophobicity and its overall surface roughness.

In this work, plasma-treated Ti-electrodes were used instead of TCO glass in DSSCs. Increasing Ti-electrode surface roughness by plasma treatment was expected to improve the adherence of TiO2 on the Ti-electrode, which may correspond to improved solar conversion efficiency in DSSCs. To the best of our knowledge, the efficacy of plasma-treated Ti-electrodes in DSSCs has not yet been studied.

10105-63, Session PWed

Electrodeposition of NiO Films from Various Solvent Electrolytic Solutions for Dye Sensitized Solar Cell Application

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The implementation of polar aprotic organic solvents and their mixture with water remains almost unexplored for the direct electrochemical deposition (ECD) of NiO. In the present work, the electrodeposition of this oxide in dimethyl sulfoxide (DMSO) and DMSO/water medium by the cathodic reduction of nickel nitrate hexahydrate is investigated. The electrochemical phenomena involved in the deposition process are clarified either in the presence and absence of water. The layers obtained in water-free and in baths containing various amounts of water have been characterized by various techniques. Thermal annealing is shown to significantly improve the structural quality of the oxide. Moreover this treatment results in layers with a mesoporous morphology and enlarged specific surface area. These layers have been sensitized by a dye and applied in p-type sensitized solar cells. Their performances have been related to the NiO electrodeposition conditions. The work illustrates the high interest of the present electrodeposition techniques for the preparation of NiO layers with enhanced properties for advanced applications.

10105-64, Session PWed

Erbium-doped ZnO, TiO2, and SiO2 nanolaminates for photonic applications

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Miniaturization of photonic components for integration with silicon photonics requires further material development in order to enhance optical gain characteristics of rare-earth materials on short length scale, while maintaining low temperature deposition and annealing processing to minimize the thermal budget on a photonics/CMOS process flow.

Concurrently, recent progress in thin film transistors based on metal oxides deposited at room temperature have shown attractive electronic devices operating in a variety of amorphous substrates, which show great promise for integration as smart optical claddings in silicon photonics.

These smart optical claddings can be integrated with thin-film transistor technology for concurrent electrical and optical sensing or optoelectronic modulation. Of further interest is the possibility to replicate at chip level, the light emitting properties of erbium doped oxides, which would allow for infrared source integration in silicon photonic chips.

In this work, we study the crystal morphology, electron transport and photo-electroluminescence of erbium-doped nanolaminates of ZnO, TiO2 and SiO2, deposited by RF-sputtering, with and without an annealing step. The effect of the nanolaminate on the interface roughness, erbium distribution on the laminate and its correlation to the photo- and electroluminescence (visible and infrared domains) is presented. A discussion on potential nanoscale electrical excitation pathways of active erbium species is also presented.

10105-65, Session PWed

Organic-inorganic mesoporous nanocomposites with enhanced sensing and optical properties

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The strong interest in graphene and carbon quantum dots (CQDs) is due to their unique properties that find application in the field of photonics and optical sensing. A viable strategy to expand the range of applications and to improve the durability of carbon-based nanostructures is represented by their incorporation into an all-inorganic or organic-inorganic matrices. Procedures based in sol-gel technology are particularly suited to this end as they enable to obtain functional composites with a high purity and to select the desired form (powder, porous or dense material, monolith or thin film) most suitable for further incorporation into C-based devices.

In this work we present a sol-gel method to produce ordered mesoporous nanocomposites containing graphene and CQDs with enhanced Raman scattering and energy transfer properties. The mesoporous nanocomposites made by organic-inorganic hybrid or functional oxides (silica, titania and zinc oxide) are obtained through a template-assisted self-assembly that permit the incorporation of pre-formed exfoliated graphene sheets or CQDs avoiding the loss of self-organization.

The physico-chemical properties of the nanocomposite materials are investigated by Transmission Electron Microscopy (TEM), N2-physisorption at 77 K, X-ray diffraction (XRD), infrared (FT-IR), UV-Vis, fluorescence and Raman spectroscopy. It is found that the synergistic effect of the carbon nanostructure and of the porous matrix leads to enhanced optical and photocatalytic properties that may find exploitation in biosensing and in environmental analyte detection and degradation. In particular, the ability of graphene to enhance the Raman scattering signal, Graphene-mediated Enhanced Raman Scattering (GERS), is found to significantly increase by embedding graphene into mesoporous titania (Ti-GERS).

10105-66, Session PWed

Mesoporous TiO2/Graphene Composite Films for the Photocatalytic Degradation of Eco-Persistent Pollutants

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TiO2 nanoparticles are suitable building blocks nanostructures for the synthesis of porous functional thin films. We report the preparation of nanocomposite layers combining anatase nanoparticles and multi-walled carbon nanotube (TiO2/MWCNT) and anatase nanoparticles and reduced graphene oxide sheets (TiO2/SGO) at various concentrations. The structure and phase composition of the layers were characterized by X-ray diffraction and Raman spectroscopy. Their morphology and texture properties were determined by scanning electron microscopy and krypton adsorption experiments, respectively. The photocatalytic performance of the layers was tested for the degradation of aqueous solutions of 4-chlorophenol serving as a model of an eco-persistent pollutant. Besides the determination of the decrease in the concentration of 4-chlorophenol, also the formation of intermediate degradation products, namely hydroquinone and benzoquinone, was followed. We show that TiO2/SGO layers had improved photocatalytic performances with a carbon content of 1.2 weight %.
The presence of MWCNTs (TiO2/MWCNT) led to a further performance improvement. Compared to a P25 reference layer, the first order rate reaction constant was increased by about 100% for the composite films containing MWCNTs at concentrations above 0.6 weight %.[1]

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10105-67, Session PWed

H2 gas sensing properties of a ZnO/CuO heterojunction

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The most important parameters of gas sensors are sensitivity and especially high selectivity to specific chemical species. To improve these parameters we developed sensors based on heterojunctions of different semiconducting materials, such as ZnO-CuO, CuO-doped SnO2-ZnO, ZnO-NiO [1-3]. In this work, the ZnO/CuO bi-layer heterojunctions were grown via a simple synthesis from chemical solution (SCS) at relatively low temperatures (< 95 °C), representing a combination of n-type and p-type semiconducting oxides which are widely used as sensing material for gas sensors. The main advantages of elaborated heterojunctions are simple synthesis and low-cost. Structural investigations showed high crystallinity of synthesized layers confirming the presence of zinc oxide nanostructures on the surface copper oxide film. Changes in morphology of grown nanostructures induced by post-growth thermal annealing were observed by scanning electron microscopy (SEM) investigations, and were studied in detail by XRD, EDX, XPS, etc. As an example of practical applications, the ZnO/CuO bi-layer heterojunctions were integrated into sensor structures and were tested with H2 gas, showing promising results for fabrication of gas sensors.

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10105-68, Session PWed

Fast vertical B-Ga2O3-based solar-blind photodetector

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?-Ga2O3 is an attractive choice for solar-blind deep ultraviolet photodetectors due to its large direct band gap of 4.8 eV (~250 nm). Moreover, its excellent chemical and thermal stability allows the use of ?-Ga2O3 in harsh environments. Despite successful demonstration of Metal-Semiconductor-Metal (MSM) photodetectors based on ?-Ga2O3, a significant drawback of such devices was their long response times. The use of a vertical Schottky structure is expected not only to improve the response times but also to increase the active area of the photodetector. Here we investigated sensitivity of vertical devices based on both bulk and thin film ?-Ga2O3. The devices exhibit low dark current of 1pA and fast response times. The top Pt electrode is formed with ~5nm semitransparent Pt layer with 50% transmittance in the solar-blind area and back surface is covered with ohmic Ti/Al metal stack. Additionally, a systematic work has been done on optimizing the etching approaches for ?-Ga2O3 including wet and dry chemical etching using photoresist, SiO2 and metal masks at various temperatures and process conditions. It was confirmed that ?-Ga2O3 has outstanding chemical stability to variety of bases and acids including HCl, HF, NHO3 and other. Phosphoric acid at 200 °C using SiO2 mask has been found to be a good applicant to etch gallium oxide with sufficient etching rate (10nm/min), uniformity and practically no under etch.

10105-70, Session PWed

Lithium-doped nickel oxide for p-type dye-sensitized solar cell applications

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No Abstract Available

10106-1, Session 1

Microlasers based on high-Q rare-earth-doped aluminum oxide resonators on silicon *(Invited Paper)*

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One of the key challenges in the field of silicon photonics remains the development of compact integrated light sources. In one approach, rare-earth-doped glass microtoroid and microdisk lasers have been integrated on silicon and exhibit ultra-low thresholds. However, such resonator structures are isolated on the chip surface and require an external fiber to couple light to and from the cavity. Here, we review our recent work on monolithically integrated rare-earth-doped aluminum oxide microcavity lasers on silicon. The microlasers are enabled by a novel high-Q cavity design, which includes a co-integrated silicon nitride bus waveguide and a silicon dioxide trench filled with rare-earth-doped aluminum oxide. In passive (undoped) microresonators we measure internal quality factors as high as 3.8 ? 105 at 0.98 μm and 5.7 ? 105 at 1.5 μm. In ytterbium, erbium, and thulium-doped microcavities with diameters ranging from 80 to 200 μm we show lasing at 1.0, 1.5 and 1.9 μm, respectively. We observe sub-milliwatt lasing thresholds, approximately 10 times lower than previously demonstrated in monolithic rare-earth-doped lasers on silicon. The entire fabrication process, which includes post-processing deposition of the gain medium, is silicon-compatible and allows for integration with other silicon-based photonic devices. Applications of such rare earth microlasers in communications and sensing and recent design enhancements will be discussed.

10106-2, Session 1

Glass and glass-ceramic photonic systems *(Invited Paper)*

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The development of optically confined structure is a major topic in both basic and applied physics not solely ICT oriented but also concerning lighting, laser, sensing, energy, environment, biological and medical sciences, and quantum optics. Glasses and glass-ceramics activated by rare earth ions are the bricks of such structures. Glass-ceramics are nanocomposite systems that exhibit specific morphologic, structural and spectroscopic properties allowing to develop new physical concepts, for instance the mechanism related to the transparency, as well as novel photonic devices based on the enhancement of the luminescence. The dependence of the final product on the specific parent glass and on the fabrication protocol still remain an important task of the research in material science. Looking to application, the enhanced spectroscopic properties typical of glass ceramic in respect to those of the amorphous structures constitute an important point for the development of integrated optics devices, including optical amplifiers, monolithic waveguide laser, novel sensors, coating of spherical microresonators, and up and down converters. This lecture presents some results obtained by our consortium regarding glass-based photonics systems. After a short history of research in glass ceramics we will comment the energy transfer mechanism in transparent glass ceramics taking as examples the up and down conversion systems and the role of SnO_2 nanocrystals as sensitizers. Coating of spherical resonators by glass ceramics, 1D-Photonic Crystals for luminescence enhancement, laser action and disordered 1-D photonic structures will be discussed. Finally, RF-Sputtered rare earth doped P_2O_5-SiO_2-Al_2O_3-Na_2O-Er_2O_3 planar waveguides, will be presented.

10106-3, Session 1

Spectroscopy of erbium-doped potassium double tungstate waveguides

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We report optically pumped crystalline waveguide amplifiers operating in the telecom C-band. Thin films of erbium-doped gadolinium lutetium

potassium double tungstate, KGd_xLu_yEr_(1?x?y)(WO_4)_2, are grown by liquid-phase epitaxy onto undoped potassium yttrium double tungstate (KYW) substrates and micro-structured by Ar+-beam etching. Channel waveguides with erbium concentrations between 0.45–6.35?10^20 cm^-3 are characterized. The transition cross-sections of interest are estimated. The effect of energy-transfer up-conversion (ETU) on the gain is experimentally investigated. Microscopic and macroscopic ETU parameters are extracted from a simultaneous analysis of 20 decay curves of luminescence on the transition 4I13/2 ? 4I15/2. The correlation between ETU and the doping concentration is studied. Pump excited-state absorption (ESA) on the transition 4I11/2 ? 4F7/2 is investigated via a direct ESA measurement using a double-modulation pump-probe technique. The effect of ESA on gain at ~1.53 µm is studied for different pump wavelengths. An optimum pump wavelength of 984.5 nm is found for the complete range of erbium concentrations. For an optimized erbium concentration of 3.8?10^20 cm^-3, a maximum relative gain of 13 dB/cm at the peak wavelength of 1534.7 nm is experimentally obtained. Lower doping concentrations yield lower gain due to gain saturation, while higher doping concentrations suffer from stronger ETU and ESA. A rate-equation model is applied to calculate the gain on the basis of the aforementioned spectroscopic parameters. Good agreement with the experimental values is obtained only when both the ESA and ETU processes are considered in the rate-equation model.

10106-4, Session 1

Co-integration of two DFB lasers on glass for millimeter-wave generation

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Future wireless communication systems will use millimeter (mm) wave frequencies carriers (30 GHz- 300 GHz) and beyond to overcome the saturation of the different frequency bands and achieve high bit rates. One of the main issues in the communication at the mm wave frequencies is generating mm-wave carrier signals.

In this work, we propose the realization of two stable single mode distributed feedback (DFB) lasers emitting at 1.5 µm with ultra-narrow linewidths, co-integrated on a co-doped Erbium Ytterbium IOG1 SCHOTT glass substrate. The beating note of these two lasers on a fast photodiode is used to generate mm-wave signals. Each laser is composed of a waveguide fabricated by ion exchange where Bragg gratings are etched on the top. In order to set a precise value of the mm wave frequency, the emission wavelength of both DFB lasers must be accurately fixed. This is achieved by controlling the laser's waveguide design. The beating produced between these lasers generates mm wave signals from GHz to THz. The co-integration helps to enhance the beating quality by reducing fluctuations between the two lasers.

Lasers are first studied independently: their optical power, linewidth and relative intensity noise are characterized and a study of laser's stability is done. Finally, the beating signal quality is estimated through the characterization of the produced electrical spectrum.

10106-5, Session 1

Temperature-dependent absorption and gain of ytterbium-doped potassium double tungstates for chip-scale amplifiers and lasers

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Ytterbium-doped potassium rare-earth double tungstate thin films are excellent candidates for highly efficient waveguide lasers, as well as high-gain waveguide amplifiers, with a record-high optical gain per unit length of 935 dB/cm demonstrated recently. However, the spectroscopic properties of these highly ytterbium-doped thin films and, in particular, their temperature dependence are not well investigated. These characteristics are required for the understanding of the behavior of the fabricated optical devices and crucial for further device optimization. We experimentally determined the absorption cross-sections for a potassium ytterbium gadolinium double tungstate, KYb0.57Gd0.43(WO4)2, thin film grown lattice matched onto an undoped KY(WO4)2 substrate. At room temperature, the peak cross-section value at 981 nm and the overall absorption spectrum are very similar to those of Yb-doped bulk potassium double tungstate crystals, although Yb is now the dominating rare-earth content. The temperature-dependent study shows a significant decrease of the absorption cross-section values at 933 nm and 981 nm with increasing temperature. We verify theoretically that this is due to the temperature dependence of fractional populations in the individual Stark levels of the absorbing crystal-field multiplet, in combination with the linewidth broadening with increasing temperature. Further investigations suggest that the broadening of absorption linewidth at 981 nm originates in the intra-manifold relaxation between the two lowest Stark levels of the ground state. Finally, the implications of the spectroscopic findings on the operating characteristics of waveguide amplifiers are investigated. Amplifiers operating at 80 °C are expected to exhibit only 67% of the maximum theoretical gain at room temperature.

10106-6, Session 2

Phase sensitive amplification in integrated chalcogenide and silicon waveguides *(Invited Paper)*

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Phase sensitive amplification (PSA) is an attractive technology for integrated all-optical signal processing, due to it's potential for noiseless amplification, phase regeneration and generation of squeezed light. In this talk I will review our results on implementing four-wave-mixing based PSA inside integrated photonic devices. In particular I will discuss PSA in chalcogenide ridge waveguides and silicon slow-light photonic crystals. We achieve PSA in both pump- and signal-degenerate schemes with maximum extinction ratios of 11 (silicon) and 18 (chalcogenide) dB. I will further discuss the influence of two-photon absorption and free carrier effects on the performance of silicon-based PSAs.

10106-7, Session 2

Low-temperature crack-free Si3N4 nonlinear photonic circuits for CMOS-compatible optoelectronic integration

Marco Casale, MINATEC (France); Sebastien Kerdiles, Vincent Hugues, Houssein El Dirani, CEA-LETI (France); Corrado Sciancalepore, MINATEC (France)

In this communication, authors report for the first time on the fabrication and testing of Si3N4 nonlinear photonic circuits for CMOS-compatible monolithic co-integration with silicon-based optoelectronics. In particular, the developed process allows fabricating low-loss dislocation-free Si3N4 730-nm-thick films for Kerr-based nonlinear functions featuring full thermal budget compatibility with existing Silicon photonics and front-end Si optoelectronics. Briefly, differently from previous and state-of-the-art works, our nonlinear nitride-based platform does not resort to commonly-

used high-temperature annealing (~1200°C) of the film and its silica uppercladding used to break N-H bonds otherwise causing absorption in the C-band and deteriorating its nonlinear functionality. Furthermore, no complex and fabrication-intolerant Damascene process - as recently reported earlier this year - aimed at controlling cracks and dislocations generated in thick tensile-strained Si_3N_4 films has been used as well. Instead, a tailored Si_3N_4 multiple-step film deposition in 200-mm LPCVD-based reactor and subsequent low-temperature (400°C) PECVD oxide encapsulation have been used to fabricate the nonlinear microresonant circuits aiming at generating optical frequency combs via optical parametric oscillators (OPOs), thus allowing the monolithic cointegration of such nonlinear functions on existing CMOS-compatible optoelectronics, for both active and passive components such as, for instance, silicon modulators and wavelength (de-)multiplexers. Experimental evidence based on wafer-level statistics shows nitride-based 50-micron-radius ring resonators using such low-temperature dislocation-free thick nitride film exhibiting quality factors exceeding Q >3 x 10^5, thus paving the way to low-threshold power-efficient Kerr-based comb sources and dissipative temporal solitons in the C-band featuring full thermal processing compatibility with Si photonic integrated circuits (Si-PICs).

10106-8, Session 2

Design and fabrication of high-Q chalcogenide glass micro-disk resonators

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Chalcogenide glass (ChG) which contain one or more chalcogen elements is one of the most interesting material for infrared (IR) photonics owing to its unique optical properties, such as high refractive index, strong optical nonlinearity, and wide infrared transparency.

In this paper, we experimentally demonstrate high-quality ChG micro-disk resonators on oxidized silicon wafers fabricated by the standard UV photolithography and lift-off. Quality factor of micro-disk resonators are often limited by optical scattering loss induced by lithographically defined edge roughness. Thermal reflow of chalcogenide itself may significantly reduce edge roughness, but thermal shrinkage and deformation of the material during the reflow make it hard to precisely control the overall size and shape of the fabricated device. Instead, we reduce the sidewall roughness using thermal reflow of photoresist and modified bi-layer lift-off process. Typically, the thermal reflow of resist destroys the undercut or vertical sidewall profile of developed resist layer, making it extremely difficult or impossible to subsequently use lift-off or etching for patterning. We address this issue by first wet etching the silica substrate to undercut the reflowed photoresist, creating an overhang required for lift-off. ChG film is then deposited to produce a micro-disk resonator with much improved edge roughness. To finally create a micro-disk resonator on a silica pillar, we adopt vapor etching of the silica substrate. With optimized conditions of reflow and undercut, we obtained high quality ChG disk-resonators with extremely smooth edge profile, operating in the infrared region. Complete characterization results will be presented at the conference. The new method is compatible with traditional CMOS process and thus expected to have great potentials for fabricating high quality photonic integrated devices.

10106-9, Session 2

feasibility study of optical parametric amplification using CMOS

compatible ring resonators

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Optical amplification is an important step toward enabling large scale CMOS compatible optical integrated circuits. One possibility is Raman amplification, which has been demonstrated in silicon waveguides [1]. An alternative is optical parametric amplification which has recently been considered for this purpose [2]. However, silicon waveguides suffer from two photon absorption (TPA) at telecom wavelengths. Because of TPA, large pump-power levels do not lead to parametric gain and there is an optimum pump-power level. However, as the pump propagates in a straight waveguide it is depleted, and therefore deviates from the optimum level, limiting the parametric gain and making it very challenging to obtain positive parametric gain with silicon nano-waveguides. Using silicon ring resonators, it is possible to store an optimum pump-power level in the ring such that the circulating signal could experience a larger gain. We show that by using parametric amplification the ring loss may be compensated, leading to signal amplification. On the other hand, ring resonators limit the operating bandwidth. In this paper we theoretically study the limits of gain and bandwidth which is achievable by parametric amplification in ring resonators.

The main advantage of ring resonators is that the power circulating in the ring could be much larger than the input pump power, depending on how close the design is to the critical coupling condition. This results in an almost arbitrary decrease in the input pump power for materials without TPA. However, an optimum design of the ring structure is necessary to obtain the desired characteristics.

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10106-10, Session 2

Integrated nonlinear optics: lithium niobate-on-insulator waveguides and resonators

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Traditionally, lithium niobate has primarily been used in the fabrication of surface acoustic wave devices and optical modulators, with its use in optics limited primarily by the lack of a method of creating low loss, high index waveguides. The waveguides of optical modulators in bulk lithium niobate, for example, are typically fabricated with a diffusion method, allowing creation of only low index waveguides with low propagation loss, but which then require very large radii for any waveguide bends. Thin film single crystal lithium niobate-on-insulator is a promising platform for future applications in integrated optics or quantum optics due to the availability of a strong electro-optic effect in this material along with high index contrast. We have fabricated and characterized low-loss waveguides, ring and racetrack resonators, gratings, and other structures in this material system that could potentially be useful in future applications requiring use of the Pockels effect. Fabrication and etching is difficult, and methods for both dry etching this material and also for reducing roughness will be described. Our group has achieved losses of less than 5 dB/cm in deeply etched (> 300 nm) waveguides.

10106-12, Session 3

Integrated polymer polarization rotator based on tilted laser ablation

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The ubiquitous need for compact, low-cost and mass production photonics devices necessitates the development of integrated components addressing functionalities that are, to date, carried out by free space elements or standard fiber equipment. The polarization rotator is a typical example of such tendency, as it is a crucial part of the polarization multiplexing schemes foreseen in future transceiver modules and high-capacity optical network scenarios. Up to now, several integrated polarization rotating concepts have been proposed, relying mainly on non-rectangular waveguide cross-sections. Nevertheless, most of those concepts employ SiPh or III-V integration platforms, significantly increasing the fabrication complexity required for engineering the shape of the waveguide, which in turn leads to either prohibitively increased cost or compromised performance.

In this manuscript we demonstrate the extensive design of a low-cost integrated polymer polarization rotator employing an intermediate segment, with right trapezoidal cross-section shape, interfaced to standard rectangular polymer waveguides. The shape of the cross-section is defined by calculating the optical axis angle of the hybrid modes excited in the intermediate segment, while iterative mode overlaps reveal the optimum lateral offset between the square polymer and the trapezoidal waveguide. The required rotator length is obtained through EigenMode Expansion propagation simulations, achieving more than 95% maximum theoretical conversion efficiency over the entire C-band. The design relies on the development of angled polymer waveguide sidewalls, utilizing the tilted laser ablation technology currently available at IMEC-CMST. To this end, the simulation methodology fully adheres to the respective design rules, taking into account the anticipated fabrication variations.

10106-13, Session 3

Cost-effective, compact and high-speed integrable multi-mode interference modulator

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The transmission through a symmetric 1x1 multi-mode interference (MMI) waveguide can be substantially suppressed by introducing a small asymmetry in the core refractive index. This can be achieved by applying a voltage in reversed bias to half of the waveguide in the lateral direction, so as to involve the anti-symmetric lateral mode, which in the unbiased situation would not participate.

Typical plots will be shown for the calculated transmission as a function of the refractive index change. For a 15 micron wide waveguide of length 472 micron and assuming only the lowest three lateral modes involved, a modulation depth of 10 dB is reached for 0.0015 index change. For a 12 micron wide, 301 micron long waveguide this modulation depth is reached for an index change of 0.0024.

In theory, a reversed-bias induced electro-optic index change of ~10-4 V-1 is feasible [2]. This means that for the 15 micron wide waveguide ~10 dB extinction ratio is feasible. As to the modulation speed, estimating the capacity of this modulator ~0.7 pF and the electric resistance <8 Ohm, the cut-off frequency will be >25 GHz. The modulator can easily be integrated with a single-mode (f.i. DFB) laser, which in case of a multi-project wafer run would be very cost affordable [3].

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10106-14, Session 3

Multiplexed wavelength-to-time conversion of multimode light

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A photonic lantern is an adiabatic guided-wave transition between a multimode waveguide and a set of single-mode cores. As such, photonic lanterns facilitate the efficient coupling of multimode light to single-mode devices, examples of which include fibre Bragg gratings and arrayed waveguide gratings. In this work, we demonstrate that photonic lanterns based on tapered multicore fibres (MCFs) provide a potentially powerful new route to efficiently couple multimode states of light to a two-dimensional array of Single Photon Avalanche Detectors (SPADs). The SPAD array consists of a 32?32 square array of pixels, each of which has its own time to digital converter (TDC) for Time Correlated Single Photon Counting (TCSPC) with a timing resolution of 55 ps. For our application, the geometry of the MCF used to fabricate the photonic lantern was chosen such that each single mode in the MCF can be mapped onto an individual SPAD pixel. Upon injecting a broad supercontinuum signal into a 290 m long MCF via a photonic lantern, wavelength-to-time mapped spectra were obtained from all modes. We believe that the techniques we report here may find applications in areas such as Raman spectroscopy, coherent LIDAR, and quantum optics.

10106-67, Session 3

Ultra-low-power stress-optics modulator for microwave photonics

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In this work, we demonstrate the first stress-optic modulator in a silicon nitride-based waveguide platform (TriPleX) in the telecommunication C-band. In our stress-optic modulator the refractive index of the waveguiding materials is controlled by the stress-optic effect induced by an actuating 2 μm thick PZT layer on top of the TriPleX waveguide geometry. The efficiency of the modulator is optimized by, amongst others, focusing the applied stress in the waveguide core region through a local increase of the top cladding. Using a Mach-Zehnder interferometer, we measured a half-wave voltage, V_ϖ, at 62 V at a wavelength of 1550 nm using a single electrode with a total length of 14.8 mm. The measured static power consumption of our stress-optic modulator is in the μW-region as it is only

determined by small leakage currents (< 0.1 μA), while the dynamic power consumption at a rise time of 1 ms (1 kHz excitation) is less than 4 mW per modulator. The stress optical modulator goes with an excess loss of 0.015 dB per modulator only. This is in line with the typical low loss characteristics of TriPleX waveguides, being < 0.1 dB/cm at a wavelength of 1550 nm. These specifications make stress-optic modulators an excellent choice for next generation optical beam forming networks in silicon photonics in general and in the TriPleX platform in particular.

10106-15, Session 4

Hybrid III-V/silicon photonic integrated circuits for high bitrates telecommunication applications *(Invited Paper)*

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Today, we are witnessing an increasing bandwidth demand in the telecom access and datacenters markets. Unlike the long haul and metropolitan networks, those two network segments are particularly sensitive to the cost and to the high-volume manufacturing compatibility of the photonic components they use. By combining the mature CMOS Silicon with the high performance III-V materials, the hybrid III-V/Silicon Photonics platform is a promising option to provide low-cost and efficient Photonic Integrated Circuits (PICs) that could meet the needs of those markets. Key components such as laser sources and fully integrated high speed transmitters are being developed.

III-V lab, together with CEA LETI, have demonstrated hybrid III-V/Si lasers using wafer-bonding technique. In this approach, unstructured InP dies are bonded, epitaxial layers down, on a SOI waveguide circuit wafer, after which the InP growth substrate is removed and the III-V epitaxial film is processed. This talk will first give a description of the fabrication technique. We will then report during this talk our recent advances on integrated hybrid InP/SOI transmitters using this process. We demonstrate the direct modulation at 10 Gb/s of different laser configurations such as wavelength tunable lasers, Distributed FeedBack (DFB) lasers and Chirp Managed Lasers. We will also present the design, fabrication and characterization of various hybrid InP/SOI transmitters integrating lasers (tunable or DFB) and modulators (silicon or III-V) with modulation up to 32 Gb/s. A brief overview of the future directions on photonic integrated circuits on Silicon will conclude this talk.

10106-16, Session 4

Epitaxial III-V/Si devices for silicon photonics *(Invited Paper)*

Dries Van Thourhout, Yuting She, Bin Tian, Zhechao Wang, Univ. Gent (Belgium); Marianna Pantouvaki, Clement Merckling, Bernadette Kunert, Weiming Guo, Joris Van Campenhout, IMEC (Belgium)

The silicon photonics platform is still missing an approach that allows to monolithically integrate efficient lasers and amplifiers in the standard process flow. Relying on an aspect ratio trapping technique whereby threading dislocations are suppressed at the boundaries of narrow trenches in a SiO2 mask and antiphase boundaries are avoided by starting the growth of V-shaped (111)-facets at the bottom of the trench we recently demonstrated high quality epitaxy of InP and GaAs on Silicon substrates. The process is selective, an important advantage of this technology in terms of integration. Starting from this material we showed lasing from InP and InP/InGaAs DFB-lasers directly grown on standard (001) silicon wafers.
In this presentation we will give an overview of these results and present further developments. Besides we will present new results from GaAs/Si devices.

10106-17, Session 4

Indium phosphide integrated photonics *(Invited Paper)*

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InP integrated photonic circuits have become a critical enabler for modern telecommunications, and by extending applicability through the use of generic integration platforms [1], they are also poised to revolutionize shorter reach communications, precision metrology, spectrometry and imaging. InP inherently offers efficient electro-optic processes, optical amplification and detection, alongside waveguiding and interferometric structures all in one chip. By using the generic building block methodology to create circuits, amplifiers, reflectors, splitters, mode-convertors and electro-optic phase shifters can be configured to create circuits from high capacity wavelength multiplexed laser transmitters and receivers through to fiber-optic sensor readouts.

Future technology nodes are expected to deliver chips operating at higher modulation bandwidths, with higher precision, with a broader range of wavelengths, higher component densities, and lower energy consumption [2]. Photonics ICs are expected to become more tightly packed, integrated and co-designed with electronic circuits and adapted for advanced packaging concepts. In this paper, we review the current status in InP integrated photonics and the research efforts for integrating the next generation of high-performance functionality.

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10106-18, Session 4

Monolithic integration of hybrid III-V/Si lasers and Si-based modulators for data transmission up to 25Gbps

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While silicon photonics has known fast developments in the last decades, the high-speed transmitters demonstrated using this technology are mostly based on external laser sources. In this communication, the 200mm silicon-on-insulator (SOI) platform is used to demonstrate the monolithic co-integration of hybrid III-V/silicon Distributed Bragg Reflector (DBR) tunable lasers and silicon Mach-Zehnder modulators (MZM) to achieve fully integrated hybrid III-V/silicon transmitters for high speed operation in the O-band. The design of each active component as well as the fabrication process steps of the whole architecture are described in details. Data transmission up to 25Gb/s (at 0km and 10km) has been reached for two different transmitter designs, with the possibility to shift the laser wavelength up to 8.5nm.

10106-19, Session 4

A photonic integrated signal processor *(Invited Paper)*

Jianping Yao D.D.S., Univ. of Ottawa (Canada)

A photonic integrated signal processor based on the InP-InGaAsP material system consisting of a bypass waveguide and three mutually coupled micro rings with each ring having two semiconductor optical amplifiers (SOAs) and a current-injection phase modulator (PM) for fully reconfigurable ultra-wideband signal processing is discussed. The signal processor can be reconfigured to perform signal processing functions including temporal differentiation, Hilbert transformation, and temporal integration. The reconfigurability is achieved by controlling the coupling between the rings and the bypass waveguide by a multi-mode interference (MMI) Mach-Zehnder interferometer (MZI) coupler and the injection currents to the SOAs. The current injection PM in a ring is used for wavelength tuning. The use of the signal processor for temporal differentiation, Hilbert transformation, and temporal integration is demonstrated. In addition to signal processing, the signal processor can also be reconfigured to operate as a signal generator. As an example, the use of the signal processor to generate a linearly chirped microwave waveform is demonstrated.

10106-20, Session 5

All-polymeric sensing platform based on packaged self-assembled bottle microresonator

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In recent years, microbottle resonators that support non-degenerate whispering gallery modes (WGMs), propagating by successive total internal reflections close to the resonator surface and all along its axis, have been widely investigated due to their potential applications in optical sensing, microlasers and nonlinear optics. To overcome some drawbacks of the standard silica microbottle resonators, we focused our attention on polymers such as SU-8 resist and NOA resins. A drop of polymeric material is dispensed onto a fiber stem, providing a mechanical support for the bottle resonator, and is photo-polymerized by an UV lamp. The interrogation system, usually constituted by a tapered silica fiber evanescently coupled with the microresonator, is substituted by a more stable planar waveguide realized in SU-8 by means of standard photolithography technique. Moreover, for guarantying the stability to surrounding disturbance of the coupling between the microbottle resonator and the planar waveguide, the fiber stem is glued to substrate. Two drilled holes in the substrate allow the rise of the glue at the ends of the fiber stem and the fixing of sensor on PMMA substrate.

In the present work, we presented an integrated full polymeric platform with self-assembled bottle microresonators packaged in a stable structure. SU-8 and NOA based microbottles are realized and morphologically characterized. The low autofluorescence emission and long term stability make the NOA based bottles suitable to be employed in a great variety of conditions. Bulk sensing measurements are performed by using water:ethanol solutions and a bulk sensitivity of 120 nm/RIU is estimated.

10106-21, Session 5

Fabrication of Bragg grating sensors in UV-NIL structured Ormocer waveguides

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We report on the fabrication of Bragg gratings in UV-NIL structured Ormocer hybrid polymer rib-type waveguides by phase mask technology and demonstrate their potential as highly sensitive temperature and refractive index sensor element.

The influence of fabrication parameters such as the applied laser fluence during the inscription process as well as the grating's length on the spectral behavior of the waveguide Bragg grating was experimentally investigated and compared to numerical simulations and calculations. By applying this technique, we found Bragg gratings with a reflectivity of up to 98 % and a -3 dB bandwidth below 150 pm to be readily achievable, which confirms the feasibility of an inscription of versatilely applicable Bragg gratings into already completed waveguide networks of Ormocers, a material-class ideally suited for an economical production of wafer scale optics.

Moreover, we demonstrate the potential of the thus fabricated optical devices as sensor elements for temperature and refractive index measurements. Here, we found the Bragg gratings to be highly sensitive towards temperature fluctuations providing a sensitivity of ca. 130 pm/°C, which corresponds to a detection limit of only 0.02 °C. The cross-sensitivity towards relative humidity was determined to be below 10 pm/%. The refractive index sensitivity of the Bragg grating sensor was found to ca. 100 nm/RIU around a surrounding refractive index of about 1.5. Thus, we consider the fabricated Bragg gratings within UV-NIL structured rib-type waveguides of inorganic-organic Ormocer hybrid polymers to be highly suitable for temperature and refractive index sensing applications.

10106-22, Session 5

SOI-based centimeter-scale Mach-Zehnder interferometers for fluid sensing

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We demonstrate centimeter-long Mach-Zehnder interferometers (MZIs) suitable for optical fluid sensing applications, fabricated on a silicon-on-insulator (SOI) platform through photolithography. The sensing mechanism is based on the perturbation, by the measurand, of the evanescent field of the optical mode in the sensing arm of the MZI. We explore two different configurations for the MZI sensing arm, a partially exposed and a fully suspended, both defined as a ridge waveguide with a 450 nm-wide and 220 nm-thick ridge on a 90 nm-thick silicon slab. The partially exposed MZI arm has oxide undercladding and air overcladding, while in the fully suspended version the buried oxide is removed through an isotropic etch. For this purpose, etch holes are defined through the slab adjacent to the waveguide. In both cases, the reference arm of the MZIs is a 450?220 nm rectangular waveguide with oxide under- and overcladding, which avoids any perturbations from the measurand. The MZIs were slightly unbalanced, with arm lengths around 1 cm. The devices were designed for TE single-mode operation around 1550 nm, and were patterned using 248 nm deep UV lithography. The sensitivity of the two structures was evaluated through mode solver simulations, and the detection limit estimated from experimental data. The calculated sensitivity of the partially exposed MZI was ~240 nm/RIU, with a detection limit of ~4.2?10-4 RIU. For the fully suspended structure, the estimated sensitivity was ~740 nm/RIU, with a detection limit of ~4.0?10-5 RIU.

10106-23, Session 5

Integrated optical sensors for 2D spatial chemical mapping

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Sensors based on optical waveguides for chemical sensing have attracted increasing interest over the last two decades, fueled by potential applications in commercial lab-on-a-chip devices for medical and food safety industries. Even though the early studies were oriented for single-point detection, progress in device size reduction and device yield afforded by photonics foundries have opened the opportunity for distributed dynamic chemical sensing at the microscale. This will allow researchers to follow the dynamics of chemical species in field of microbiology, and microchemistry, with a complementary method to current technologies based on microfluorescence and hyperspectral imaging.

The study of the chemical dynamics at the surface of photoelectrodes in water splitting cells are a good candidate to benefit from such optochemical sensing devices that includes a photonic integrated circuit (PIC) with multiple sensors for real-time detection and spatial mapping of chemical species.

In this project, we present experimental results on a prototype integrated optical system for chemical mapping based on the interaction of cascaded resonant optical devices, spatially covered with chemically sensitive polymers and plasmon-enhanced nanostructured metal/metal-oxide claddings offering chemical selectivity in a pixelated surface. In order to achieve a compact footprint, the prototype is based in a silicon photonics platform. A discussion on the relative merits of a photonic platform based on large bandgap metal oxides and nitrides which have higher chemical resistance than silicon is also presented.

10106-24, Session 6

Recent advances in hybrid VO2/Si devices for enabling electro-optical functionalities *(Invited Paper)*

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In the last years the integration of active materials on silicon photonics has attracted a growing interest for pushing forward the performance of current photonic devices. Active materials allow tuning their optical properties by means of an external signal. Amongst them, vanadium dioxide (VO2) has been largely investigated for different applications due to its controllable change between an insulator and a metallic phase. For photonic applications, VO2 shows a promising performance due to the ultra-large change in the refractive index across the two phases in the metal-to-insulator transition (MIT). In this work, we will present the recent advances in hybrid VO2/Si devices for enabling electro-optical functionalities.

10106-25, Session 6

Monolithic photonic integration technology platform and devices at wavelengths beyond 2μm for gas spectroscopy applications *(Invited Paper)*

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In this paper a generic monolithic photonic integration technology platform and tunable laser devices for gas sensing applications at 2μm will be presented. The basic set of long wavelength optical functions which is fundamental for a generic photonic integration approach is realized using planar, but-joint, active-passive integration on indium phosphide substrate with active components based on strained InGaAs quantum wells. Using this limited set of basic building blocks a novel geometry, widely tunable laser source was designed and fabricated within the first long wavelength multi-project wafer run. The fabricated laser operates around 2027nm, covers a record tuning range of 31nm and is successfully employed in absorption measurements of carbon dioxide. These results demonstrate a fully functional long wavelength photonic integrated circuit that operates at these wavelengths. Moreover, the process steps and material system used for the long wavelength technology are almost identical to the ones which are used in the technology process at 1.5μm which makes it straightforward and hassle-free to transfer to the photonic foundries with existing fabrication lines. The changes from the 1550nm technology and the trade-offs made in the building block design and layer stack will be discussed.

10106-26, Session 6

Ultra-low-loss and broadband mode converters in Si3N4 technology

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Si3N4 grown by LPCVD on thermally oxidized silicon wafers is largely utilized for creating integrated photonic devices due to its ultra-low propagation loss and large transparency window. This paper presents the optimal design of an ultra-low-loss and broadband mode converter for hybrid integration applications on Si3N4 technology. It is constructed with a vertically tapered Si3N4 waveguide buried by a polymer waveguide core. The calculated loss of the optimal converter is less than 0.3 dB at 980 nm and 1550 nm wavelengths. The experimental results match well with the design values.

10106-27, Session 6

Relaxed tolerance adiabatic silicon coupler for high I/O port-density optical interconnects

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Widespread deployment of silicon photonics will benefit strongly from improved high-port-density interconnect solutions between chips, interposers, and other waveguide fabrics. We present an adiabatic silicon waveguide to polymer waveguide coupler design incorporating strong vertical asymmetries offering high efficiency, small footprint, and improved tolerance to lateral misalignment. The design incorporates a standard 450nm-wide silicon waveguide tapered down to 50nm over a distance of

200μm with a 1.6μm-thick polymer waveguide having a 4μm-wide core atop the taper. The coupler exhibits <0.1dB loss for both TE and TM modes based on 3-dimensional finite element modeling. Moreover, the modeled device exhibits less than 0.1dB excess loss with lateral misalignment of +/–2μm between polymer and silicon waveguide for TE mode, and 0.2dB excess loss with +/–1.6μm offset for the TM mode, and 1dB excess loss for both TE and TM modes with +/–2.7μm misalignment. This taper design should enable reduction in manufacturing costs due to a reduced on-chip footprint and the potential for lower-precision, higher-throughput assembly tools. The authors would like to acknowledge the support of AIM Photonics. This material is based on research sponsored by Air Force Research Laboratory under agreement number FA8650-15-2-5220. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of Air Force Research Laboratory or the U.S. Government.

10106-28, Session 7

Spectroscopic sensing with silicon nitride photonic integrated circuits *(Invited Paper)*

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Silicon photonics is rapidly emerging as a mature technology platform for the fabrication of photonic integrated circuits. It builds on the technology base of the CMOS-world and allows to implement advanced photonic functions on a small footprint chip with high accuracy and yield. For operation at telecom wavelengths above 1 micrometer one typically uses silicon-on-insulator wafers with waveguides with a silicon core. For short-wavelength operation, below 1 micrometer, one can use a silicon nitride (SiN) core instead of a silicon core. This results in a platform for operation in the visible and near infrared, with moderately high refractive index contrast and low loss photonic components. Operation at short wavelengths can be beneficial for a variety of reasons, including the possibility to use low cost high performance sources and detectors and the compatibility with sensing in an aqeous environment.

The SiN CMOS-platform has been used to demonstrate a variety of spectroscopic sensing functions. In essence the SiN chips may contain sensing structures, whereby the evanescent tail of the guided light is interacting with the analyte, as well as spectrometric functions to read out the spectrum resulting from the interaction with the analyte. This approach has allowed to demonstrate refractive index biosensors, spontaneous Raman spectroscopy and surface-enhanced Raman spectroscopy. In the latter case the SiN waveguides are enriched with gold nano-antennas to enhance the local field strength seen by the analyte. The spectrometric functions can be based on arrayed waveguide gratings, echelle grating spectrometers or Fourier Transform spectrometers.

10106-29, Session 7

Optofluidic sensor engineering towards dilute Pu concentration measurements

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Research in nuclear safety and fuel reprocessing has led to a surging need for novel chemical analysis tools with reduced analyte volumes. Recent technological advances for the elaboration and packaging of glass optofluidic sensors have opened up the way for on-chip analysis in harsh environments. Co-integrated sensors are elaborated with micromachining techniques, ion-exchange and substrate bonding technologies in order to provide microfluidic analysis while withstanding elevated acidity and radiation constraints. We introduce a waveguide engineering approach for the construction of an integrated absorption detection cell with an ion-exchanged core. We direct our study towards the quantified detection of plutonium (Pu) absorption peaks in the 700 to 900 nm range.

Pu(IV) and Pu(VI) oxidation states exhibit absorption peaks around 800 nm with molar absorption coefficients of 20 L.mol-1.cm-1 and 545 L.mol-1.cm-1 respectively. An evanescent waveguiding structure that allows guided fluid/light interaction is studied in order to determine detection feasibility of each Pu oxidation state with the co-integrated sensor. This ensues the study of the field/fluid interaction coefficient ?. Additional investigation is made towards signal losses and waveguide single-mode behavior to analyze signal/noise ratio. The work presented consists of optical simulations as well as optical characterization of elaborated sensors.

10106-30, Session 7

Slow-light enhanced chemical sensing with an on-chip Fano system

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Integrated silicon photonics promises efficient on-chip solutions for chemical and bio-molecule sensing for faster and reliable disease diagnostics. By integrating a sensor with a light source and a detector, a compact lab-on-chip sensing device is possible to realize. To increase the sensing efficiency, slot waveguide geometry is preferable due to the high confinement of the mode within the cover material.

When two different light-paths in a structure interfere with each other, causing the superposition of a Lorenzian response with the background radiation continuum, a Fano lineshape occurs. This sharp resonance leads to a superior refractive index sensing capability.

To develop a compact on-chip Fano-resonant platform for chemical sensing, we used a merged photonic crystal – slot waveguide (MPCSW) structure as the basic building block. It contains slot waveguides merged with Bragg gratings, formed by periodic patterning of the rails. A defect between the two Bragg grating sections forms a resonant cavity. In addition to the enhancement due to the confinement of light in the slot waveguide, the highly dispersive nature of the Bragg grating leads to slow light effect at the resonance. Three MPCSW structures are parallel-coupled to form an on-chip Fano system. By changing the refractive index of the cover material, we found a sensitivity as high as 775 nm/RIU. Moreover, the group index at the resonance of our Fano system is as high as ng = 500, due to the effect of slow light. We obtain vast increase in the refractive index sensitivity of the device.

10106-31, Session 7

Silicon oxynitride-on-glass waveguide array refractometer with wide sensing range and integrated read-out

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In this work, a silicon oxynitride-on-silica refractometer is presented, based on sub-wavelength coupled arrayed waveguide interference, and capable of low-cost, high resolution, large scale deployment. The sensor has an experimental spectral sensitivity as high as 3200 nm/RIU, covering refractive indices ranging from 1 (air) up to 1.43 (oils). The sensor readout can be performed by standard spectrometers techniques of by pattern projection onto a camera, followed by optical pattern recognition. Positive identification of the refractive index of an unknown species is obtained by pattern cross-correlation with a look-up calibration table based algorithm. Given the lower contrast between core and cladding in such devices, higher mode overlap with single mode fiber is achieved, leading to a larger coupling efficiency and more relaxed alignment requirements as compared to silicon photonics platform. Also, the optical transparency of the sensor in the visible range allows the operation with light sources and camera detectors in the visible range, of much lower capital costs for a complete sensor system. Furthermore, the choice of refractive indices of core and cladding in the sensor head with integrated readout, allows the fabrication of the same device in polymers, for mass-production replication of disposable sensors.

10106-32, Session 7

Integrated lab-on-a-chip sensor using shallow silicon waveguide multimode interference (MMI) device

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The objective of this work is to develop an integrated general purpose label-free optical sensor using standard photolithography for lab on chip applications. Shallow silicon waveguides (SSW) have poor confinement in the silicon with lots of field in the cladding. This is advantageous in sensor applications due to the high light matter interaction. Here, we use our shallow strip waveguide platform to design a sensor employing a multimode interference (MMI) section. Due to the very low propagation loss of 0.2 dB/mm, it is very easy to optimize the sensor for a specific application to target the required sensitivity while enjoying low insertion loss. We used Eigenvalue Mode Expansion (EME) solver in Lumerical Mode Solutions to study the trade-offs and optimize our design. Utilizing a multi-mode section as short as 4 mm, the sensor exhibits an extinction ratio of 7.2 dB for a 0.01 change in the cladding refractive index while the insertion loss is less than 1 dB.

10106-33, Session 8

Multiplexing photonic devices integrated on a silicon/germanium platform for the mid-infrared *(Invited Paper)*

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With the recent progress in integrated silicon photonics technology and the recent development of efficient quantum cascade laser technology (QCL), there is now a very good opportunity to investigate new gas sensors offering both very high sensitivity, high selectivity (multi-gas sensing, atmosphere analysis) and low cost thanks to the integration on planar substrate. In this context, we have developed singlemode optical waveguides in the mid-infrared based on Silicon/Germanium alloy integrated on silicon. These waveguides, compatible with standard microelectronic technologies present very low loss in the 3300cm-1 – 1300 cm-1 range.

This paper will present the design, technological realization, and characterization of array waveguide grating devices and planar concave gratings specifically developed for the simultaneous detection of several gas using arrays of QCL sources. Gas sensing generally require a tuneable source continuously covering the whole operational range of the QCL stack. With this objective, specific design has been adopted to flatten the optical transfer function of the multiplexers. Samples devices around 2235cm-1 were realized and tested and showed results in good agreement with the modeling, flat transmission over a full 100 cm-1 operational range were obtained with a peak-to-valley modulation of -5dB were experimentally measured. These devices will be soon associated with QCL arrays in order to provide integrated, powerful, multi wavelength, laser sources in the 2235 cm-1 region applicable to NO, CO, and CO2 multi-gas sensor.

10106-34, Session 8

All-optical processing using phase-change nanophotonics *(Invited Paper)*

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Nanophotonic integrated circuits allow for realizing functional optical devices using efficient design and fabrication routines. Their inherent stability and scalability makes them attractive for applications where optical signal processing is combined with coupling to external light stimuli. A majority of nanophotonic devices is, however, based on passive materials, which do not provide low-power tuning options or knobs for reconfigurability. We address this shortcoming by combining passive silicon nitride photonic devices with tunable phase-change materials. Such a platform allows realizing both on-chip optical data storage and active photonic components. Multi-level photonic memories with random access would allow for leveraging even greater computational capability. Thus far, photonic memories have been predominantly volatile, meaning that their state is lost once the input power is removed. By using optical near-field coupling within on-chip waveguides, we realize bit storage of up to eight levels in a single device that readily switches between intermediate states. We show that individual memory elements can be addressed using a wavelength multiplexing scheme. Such multi-level, multi-bit devices provide a pathway towards eliminating the von Neumann bottleneck and portend a new paradigm in all-photonic memory and non-conventional computing. We further show that such devices can be operated with short optical pulses, both for write and read operations.

10106-35, Session 8

Development of sol-gel saturable absorber for integrated Q-switched lasers

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The diversity of integrated photonic sensors such as LIDARs, OCT devices, lab on chips increased thanks to the development of new integrated laser sources. Glass integrated lasers fit optical sensing demand because of their high durability and integrability. We are interested here in improving durability and output power of solid-state integrated Q-switched lasers using sol-gel saturable absorbers.

While sol-gel materials are already used to produce reverse saturable absorbers for optical limiting devices, their use as a host for saturable absorber has not been investigated so far. Due to its interesting properties such as chemical resistance, suitable laser induced damage threshold (LIDT), coating convenience, it is thus also a good candidate to fabricate reliable saturable absorber matrix.

We mixed hybrid mineral-organic sol with toluene and (bis(4_ dimethylaminodithiobenzil) nickel – BDN I, a saturable absorber dye molecule. 100µm thick layers of this material have been coated and annealed to obtain a saturable absorber sol-gel. We measured absorption of these layers versus optical input power at the wavelength of 1064nm in order to extract its spectroscopic parameters: absorption cross sections and relaxation time. This saturable absorber showed good performance with over 30% of modulation depth and over 20J/cm? LIDT. A study of the influence of annealing and UV-insulating process on LIDT is presented.

This sol-gel has also been spin coated on glass substrates containing ion exchanged waveguides. We measured saturable absorption characteristics of these devices. This allowed us to create a model for saturable absorber waveguides, which can be used to design integrated Q-switched laser.

10106-36, Session 8

Integrated graphene photodetector based on a gate- controlled pn- junction

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The integration of electrical and optical components on a single chip, favourable silicon, is a major goal in research. Thereby, a bottleneck is the integration of active and passive optical elements. Graphene, with its electrically tuneable absorption and ultrafast photoresponse, is a promising candidate to move a step closer towards high-speed on-chip integration.

We fabricated a dual-gate tuneable pn-junction graphene phototdetector to investigate the relevant conversion mechanisms. The photodector is integrated on a silicon slot waveguide, which has twofold function. First, the two silicon strips of the slot waveguide are utilized as dual gate electrodes to create an electrically controllable pn-junction in the graphene. Second, the slot waveguide design allows confinement of light in subwavelength dimension. The confined light is directly absorbed in the slot between the n- and p-doped regions. At zero bias the conversion is dominated by the photo-thermoelectric effect, where we achieved a responsivity of 35 mA/W. While by applying a low bias of 300 mV, the responsivity increased to 76 mA/W due to an additional photoconductive contribution.

The photoresponse of photodetectors based on the photo-thermoelectric effect arises from hot electrons, rather than lattice heating. Therefore, we could demonstrate that our graphene integrated photodetector based on a tuneable pn-junction reaches a setup-limited 3dB-bandwidth of 65 GHz, which is the highest value reported for a graphene-based phototedetector.

10106-37, Session 8

Light-driven liquid microlenses

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We propose a liquid polymeric compound based on photo-responsive azo-polymers to be used as light activated optical element with tunable and reversible functionalities. The interaction of a laser beam locally modifies the liquid density thus producing a refractive index gradient. The laser induced refractive index profiles are observed along the optical axis of the microscope to evaluate the total phase shift induced and along the orthogonal direction to provide the axial distribution of the refractive index variation. The focusing and imaging properties of the liquid lenses as functions of the light intensity are discussed.

Traditional imaging optical elements are static in nature and the focusing is typically achieved by physical displacement of the lenses. In recent years an increasing demand for adaptive optical elements whose properties can be actively tuned has led to develop the concept of liquid micro-lenses. Such systems are typically based on pre-fabricated membranes whose shape can be controlled by an external stimulus (pressure variations, electro-wetting). More recently, the use of smart materials such as thermo-responsive or pH responsive hydrogels has been proposed to modify the shape of such pre-structured membranes to tune their optical properties.

Here we propose a polymeric liquid system that do not requires any pre-structuration and whose optical properties can be reversibly triggered by light intensity. A liquid polymeric compound based on photo-responsive azo-polymers is used as the active material. When illuminated by radiation at proper wavelength and power, a refractive index change is produced according to the beam transverse intensity distribution. As these liquid elements can be included in optical imaging systems, their properties are discussed, including the reversibility of the process and the relaxation time.

10106-38, Session 9

Multilayered metal-insulator nanocavities: toward tunable multi-resonance nano-devices for integrated optics *(Invited Paper)*

Wei Zhou, Junyeob Song, Virginia Polytechnic Institute and State Univ. (United States)

A core goal of information technology is to alleviate the bottleneck between fiber-based optical networks for telecommunication and semiconductor-based devices for data generation, processing, routing, and storage. Accomplishing this will require the accelerated development of low-cost, compact, energy-efficient optoelectronic and nonlinear-optical devices for faster information handling and transfer. Plasmonic nanoresonators and nanoantennas can control light flows and enhance light-mater interactions at subwavelength scale, and thus can potentially be used as nanoscale components in integrated optics systems either for passive optical coupling, or for active optical modulation and emission. Here we investigated a new type of multilayered metal-insulator optical nanocavities that can support multiple localized plasmon resonances with ultra-small mode volumes. The total number of resonance peaks and their resonance wavelengths can be freely and accurately controlled by simple geometric design rules. Multi-resonance plasmonic nanocavities can serve as a wavelength-multiplexed nanoantennas to couple light into or out of optical waveguides. Furthermore, radiation rates and modulation speeds of light emitting devices can be selectively and simultaneously enhanced at multiple wavelengths by such multi-resonance plasmonic nanocavities through Purcell effects.

10106-39, Session 9

Titanium nitride based hybrid plasmonic-photonic waveguides for on-chip plasmonic interconnects

Aveek Dutta, Soham Saha, Nathaniel Kinsey, Purdue Univ. (United States); Urcan Guler, Purdue University (United States); Vladimir M. Shalaev, Alexandra Boltasseva, Purdue Univ. (United States)

Conventional plasmonic materials like gold and silver have been extensively used for demonstrations of Long-Range Surface Plasmon Polariton (LRSPP) waveguides, dielectric-loaded waveguides, V-groove and metal-insulator-metal slot waveguides, etc. for chemical sensing and/or on-chip plasmonic interconnects and modulators. However, these metals are not CMOS compatible and so processing them using established nano-fabrication techniques is not a viable option. This has led to the growth of research in the field of alternate plasmonic materials. Titanium Nitride is an excellent material in this category as it is CMOS compatible, bio-compatible and can be grown epitaxially on substrates like c-axis Sapphire.

In this work we demonstrate hybrid-plasmonic waveguides made of TiN on Sapphire, cladded with Silicon Nitride. A 10nm TiN film was deposited on a Sapphire substrate using DC Magnetron Sputtering at 8000 C in an Argon-Nitrogen environment. Ellipsometry measurements showed a permittivity of -59+24i at 1.55um wavelength. The film was patterned with photolithography and dry etched using a Chlorine-based recipe to get strips of width 8.7?m. A top cladding of 340nm Silicon Nitride was then deposited. The waveguides were tested at 1.55?m wavelength using a white-light laser source with a bandpass filter, polarizer and polarization controller. The waveguides had an extinction ratio of 4.5 between TE and TM polarization, with a measured mode size around 12?m and a propagation length of 7.2mm which matched well with simulation results. The obtained results are an improvement on previously published results on Gold and TiN LRSPP waveguides of comparable widths and thicknesses. Moreover, our design provides potential for realizing on-chip plasmonic interconnects on an all-solid-state platform using CMOS compatible materials.

10106-40, Session 9

A directional coupling scheme for efficient coupling between Si3N4 photonic and hybrid slot-based plasmonic waveguides

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Slot-based plasmonic waveguides have attracted significant attention owing to their unique ability to confine light within nanometer-scale slot structures. Enhanced localized light-matter interaction and control have been exploited to demonstrate novel concepts in data communication and sensing applications revealing the immense potential of plasmonic slot waveguides. However, inherent light absorption in the metallic slot hampers the scaling of plasmonic devices and limits their application diversity. Hybrid plasmonic-photonic slot waveguides have been introduced as the means to reduce propagation losses while maintaining their functional advantages. In addition, the co-integration of such structures with lowloss photonic waveguides, will enable the development of more complex structures with acceptable overall losses. In such scenario, light needs to be efficiently transferred from the photonic to the plasmonic components and backwards.

In this work, a hybrid plasmonic structure is adopted to achieve highly efficient light transfer between photonic and plasmonic slot waveguides in the near-infrared spectrum region (1550 nm) with the aid of a directional coupling scheme. For this purpose, a Si3N4 bus waveguide (photonic branch) is located below an Au-based metallic slot (plasmonic branch) forming a hybrid waveguide. It is shown, with the aid of numerical simulations that, the combined configuration supported two hybrid guided modes with even and odd symmetry allowing the development of a power exchange mechanism between the two branches. In this context, a new directional coupling configuration has been designed which can achieve power transmission per transition over 68% within a coupling length of the order of just several microns.

10106-41, Session 9

Butt-coupled interface between stoichiometric Si3N4 and thin-film plasmonic waveguides

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Plasmonic technology has emerged as the most promising candidate to revolutionize future photonic-integrated-circuits (PICs) and deliver performance breakthroughs in diverse application areas by providing increased light-matter interaction at the nanometer scale, overcoming the diffraction limit. However, high insertion losses of plasmonic devices impede their practical deployment in PICs. To overcome this hurdle, selective integration of individual plasmonic devices on low-loss photonic platforms is considered, allowing for enhanced chip-scale functionalities with realistic power budgets. In this context, highly-efficient and fabrication-tolerant optical interfaces for co-planar plasmonic and photonic waveguides become essential, bridging these two “worlds” and ease combined high-volume manufacturing. Herein, we propose by means of 3D FDTD numerical simulations, a TM-mode butt-coupled interface for stoichiometric Si3N4 and Au-based thin-film plasmonic waveguides for biosensing applications. Numerical results demonstrated coupling efficiencies up to 64% at 1.55 ?m, with increased fabrication tolerance compared to silicon based waveguide alternatives. More specifically, a 360x800 nm strip Si3N4 waveguide top cladded with Su8 is tapered up to 7.5 ?m so as to provide spatial and modal matching with the plasmonic mode supported by the 0.1x7 ?m metal thin-film exposed in water. Structural parameter optimization was conducted with respect to the vertical and lateral offset between the photonic and plasmonic waveguide edges. Deviations from the optimal structural parameters of 500 nm and ±100 nm, introduced additional loss of less than 4% at 1.55 ?m for lateral and vertical offset, respectively. The proposed interface is currently being fabricated for experimental verification.

10106-42, Session 10

Nonlinear optical modulation in a plasmonic Bi:YIG Mach-Zehnder interferometer

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A novel method for manipulation of integrated optical modes involves the use of magneto-optic (MO) materials. A transversely magnetized waveguide incorporating a MO medium will induce a nonreciprocal phase shift (NRPS) onto the mode. Application of time-varying magnetic fields can drive the magnetization of the material, and correspondingly change the NRPS. In a Mach-Zehnder interferometer, this influences the output interference. Here, we present the design and simulation of a magnetoplasmonic MZI, based on long-range dielectric-loaded plasmonic waveguides constructed from bismuth-substituted yttrium iron garnet (Bi:YIG). The magnetization of this garnet is driven with RF magnetic fields generated by current signals passing through nearby transmission lines. As such, the temporal evolution of the magnetization within the Bi:YIG is driven in a highly nonlinear manner, prescribed by the Landau-Lifshitz-Gilbert model. The nonlinear dynamics of the transverse magnetization component are mapped onto the output optical intensity through the NRPS. We show that the frequency spectrum

of the output modulated intensity signal develops new spectral components through these nonlinear interactions. Specifically, when driving the device at a single frequency, the device can be tuned to display harmonic generation, frequency splitting, and frequency down-conversion. Driving the device at two frequencies simultaneously will mix the two RF signals. This tunable and versatile device can be utilized to generate optical modulation at a number of distinct frequencies with only one or two driving signals, and is envisioned to reduce the number of electrical sources required on chip for encoding data at different frequencies.

10106-43, Session 10

Graphene-based plasmonic slot electro-optic modulator

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Graphene, as the first identified two dimensional material, has shown great electro-optic response via Pauli-blocking for near IR frequencies and modulating functionality. However, this ability to modulate light is fundamentally challenged by its small optical cross-section leading to miniscule modal confinement factors in diffraction-limited photonics despite intrinsically high electro-optic absorption modulation (EAM) potential given by its strong index change. Yet the inherent polarization anisotropy in graphene and device tradeoffs lead to additional requirements with respect to electric field directions and modal confinement. The extinction ratio of graphene based EAM has, so far, been limited due to the small light matter interaction given the monolayer structure nature. Here we report an ultra-compact graphene based EAM by integrating graphene with a plasmonic slot waveguide. We show that the modal confinement and hence the modulation strength of a single-layer modulated graphene in this plasmonically confined mode is able to improve by more than 10x compared to diffraction-limited modes. Combined with the strong-index modulation of graphene the modulation strength could achieve more than 1dB/um, which is more than 2-orders of magnitude higher compared to Silicon platform graphene modulators. Furthermore, the modal confinement was found to be synergistic with performance optimization via enhanced light-matter-interactions. These results show that there is room for scaling 2D material EAMs with respect to modal engineering towards realizing synergistic designs leading to high-performance modulators.

10106-44, Session 10

Plasmonics-enabled metal-semiconductor-metal photodiodes for high-speed interconnects and polarization sensitive detectors

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Metal-semiconductor-metal (MSM) photodiodes are commonly used in ultrafast photoelectronic devices. Recently it was shown that localized surface plasmons can sufficiently enhance photodetector capabilities at both infrared and visible wavelengths. Such structures are of great interest since they can be used for fast, broadband detection. By utilizing the properties of plasmonic structures it is possible to design photodetectors that are sensitive to the polarization state of the incident wave. The direct electrical readout of the polarization state of an incident optical beam has many important applications, especially in telecommunications, bio-imaging and photonic computing. Furthermore, the fact that surface plasmon polaritons can circumvent the diffraction limit, opens up significant opportunities to use them to guide signals between logic gates in modern integrated circuits where small dimensions are highly desirable. Here we demonstrate two MSM photodetectors integrated with aluminum nanoantennas capable of distinguishing orthogonal states of either linearly or circularly polarized light with no additional filters. The localized plasmon resonances of the antennas lead to selective screening of the underlying silicon from light with a particular polarization state. The non-null response of the devices to each of the basis states expands the potential utility of the photodetectors while improving precision. We also demonstrate a design of waveguide-coupled MSM photodetector suitable for planar detection of surface plasmons.

10106-45, Session 10

Surface plasmon resonance sensor using vari-focal liquid lens under angular interrogation

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In this paper, a surface plasmon resonance sensor for the detection of refractive index variation is presented. A novel waveguide type surface plasmon resonance sensing configuration with focal length variable liquid lens is introduced. The method of surface plasmon resonance sensor is based on the waveguide type with incident angle variation. The incident angle is varied by using an electrowetting liquid lens which is possible to actively change focal length as applying voltage. The optical system, which is adapted to electrowetting lens can continuously change the incident angle of light from 0 to 90 degrees with compact size. The sensing surfaces are prepared by coating of gold metal above high refractive index glass substrate. The incident light which is 633nm monochromatic light source passes through a noble metal coated substrate to detect intensity with incident angle variation. An analysis to distinguish the contribution of light with various incident angle is focused on the angular characteristics of the surface plasmon sensor under wavelength interrogation. The resonance angle is determined corresponding to sensing material refractive index with high sensitivity. The result suggests that the performance of surface plasmon resonance sensor can be improved by real time varying incident angle. From this presented study, it provides a different approach for angular interrogation surface plasmon resonance sensor and can be miniaturized for a portable devices.

10106-11, Session 11

Exploring optical isolation and nonreciprocity with resonators *(Invited Paper)*

JunHwan Kim, Seunghwi Kim, Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)

Microscale resonators that simultaneously exhibit high-Q optical and mechanical resonances are routinely used to study the coupling between light and vibration. We have learned recently that Brillouin scattering (traveling-wave light-sound interactions) within simple dielectric whispering-gallery resonators can enable nonreciprocal optical transmission through a waveguide, which can be reconfigured optically and on demand. In this talk, we describe the basic theory and experimental demonstrations of Brillouin Optomechanics, and describe how it allows the breaking of time-reversal symmetry by means of traveling phonon modes. We experimentally demonstrate ultra-low loss optical isolation using a simple resonator system. Our results demonstrate that chip-scale optical isolation is much more accessible than previously thought.

10106-46, Session 11

Engineering complex nanolasers: from spaser quantum information sources to near-field anapole lasers *(Invited Paper)*

Juan Sebastian Totero Gongora, King Abdullah Univ. of Science and Technology (Saudi Arabia); Andrey Mrioshnichenko, Yuri S. Kivshar, The Australian National Univ. (Australia); Andrea Fratalocchi, King Abdullah Univ. of Science and Technology (Saudi Arabia)

In this invited contribution I will review some recent results of our research in the field of complex nanolasers. I will begin by discussing recent experimental results from a new type of ultra-dark nanoparticles, which behave as an ideal black-body [Nat. Nanotech 11, 60 (2016)]. In a series of experiments we show how such dark system is able to spontaneously produce single color pulses thanks to a dynamics that is fully equivalent to a Bose-Einstein Condensation of light. Recent developments in quantum simulators require the realization of coherent sources at the nanoscale. By quantitatively studying the lasing emission from a core-shell spaser nanoparticle, we illustrate how is possible to design new quantum information sources that allow to control the emission pattern of the system [Laser & Photonics Reviews 10, 432 (2016)]. In recent years, the possibility of developing invisibile devices with metamaterials has stirred great interest. While most of the research is devoted to realize passive invisible objects, an intriguing question is the possibility to develop an electromagnetic source that does not radiate in the far-field. This source is expected to possess a very low laser threshold, thereby opening new applications of nanolasers in the near field. This is particularly interesting in the field of silicon photonics. We here illustrate how such "Anapole laser" can be conceived, discussing many applications of this new type of integrated source for optical light manipulation at the nanoscale.

10106-47, Session 11

Observing quantum interference in 3D integrated-photonic symmetric multiports

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The investigation of multi-photon quantum interference in symmetric multi-port splitters has both fundamental and applicative interest. Destructive quantum interference in devices with specific symmetry leads to the suppression of a large number of possible output states, generalizing the Hong-Ou-Mandel effect; simple suppression laws have been developed for interferometers implementing the Fourier or the Hadamard transform over the modes. In fact, these enhanced interference features in the output distribution can be used to assess the indistinguishability of single-photon sources, and symmetric interferometers have been envisaged as benchmark or validation devices for Boson-Sampling machines.

In this work we devise an innovative approach to implement symmetric multi-mode interferometers that realize the Fourier and Hadamard transform over the optical modes, exploiting integrated waveguide circuits. Our design is based on the optical implementations of the Fast-Fourier and Fast-Hadamard transform algorithms, and exploits a novel three-dimensional layout which is made possible by the unique capabilities of femtosecond laser waveguide writing.

We fabricate devices with m=4 and m=8 modes and we let two identical photons evolve in the circuit. By characterizing the coincidence output distribution we are able to observe experimentally the known suppression laws for the output states. In particular, we characterize the robustness of this approach to assess the photons' indistinguishability and to rule out alternative non-quantum states of light.

The reported results pave the way to the adoption of symmetric multiport interferometers as pivotal tools in the diagnostics and certification of quantum photonic platforms.

10106-48, Session 11

Four-channel interferometry with a zig-zag array of mid-infrared integrated waveguides

Romina Diener, Friedrich-Schiller-Univ. Jena (Germany); Jan Tepper, Univ. zu Köln (Germany); Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany); Lucas Labadie, Univ. zu Köln (Germany); Stefano Minardi, Friedrich-Schiller-Univ. Jena (Germany) and innoFSPEC Potsdam (Germany)

Integrated optics (IO) multi-field interferometers have recently gained a lot of interest for scientific and industrial applications ranging from biosensors, to quantum computing, and stellar interferometry. The main advantage of integrate optics platforms lies in the possibility to deliver highly stable interferometric beam combination functions with miniaturized size and virtually no maintenance requirements. Besides conventional planar IO photolithographic technologies, these components can be manufactured by means of ultrafast laser inscription (ULI), a IO technology offering extension of the operating wavelength beyond the near-infrared and 3D, micro- nano-structuring capabilities as well. In particular, this last feature allows for the design simplification of IO multi-field beam combiners by waveguide crossings avoidance or by exploitation of the properties of 2D arrays of straight waveguides.

In this work, we present near-field and interferometric characterization of the first samples of a mid-infrared 4-channel interferometric beam combiners consisting in a simple 2D periodic array of coupled waveguides. The samples were manufactured by ULI in Gallium Lanthanum Sulfide (GLS) glass and feature a chain of 23 waveguides arranged on a zig-zag lattice. The foreseen application is the combination of telescopes for spectro-interferometric imaging of astronomical targets, but the results are of more general interest for applications in biophotonics and quantum optics. Advantage of the proposed design is the use of straight waveguides and short propagation lengths (up to 2 coupling lengths) required to combine a large number of channels, potentially enabling overall propagation losses below 1-2 dB.

10106-49, Session 11

Subpicometer thermal shifts in silicon photonic micro-ring resonators with sol-gel claddings

Soha Namnabat, Kyung-Jo Kim, The Univ. of Arizona (United States); Adam M. Jones, Sandia National Lab. (United States); Roland Himmelhuber, The Univ. of Arizona (United States); Christopher T. DeRose, Andrew Pomerene, Tony L. Lentine, Sandia National Labs. (United States); Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States)

Electronic interconnects are reaching their limit in terms of speed, dimensions and permissible power consumption. This has been a major concern in data centers and large scale computing platforms, creating limits to their scalability especially with respect to power consumption.

Silicon photonic-electronic integration is viewed as a viable alternative that enables reliability, high efficiency, low cost and small footprint. In particular, silicon with its high refractive index, has enabled the integration a many individual optical elements (ring resonators) in small areas. Though silicon has a high thermo-optic coefficient (1.8?10^-4/°C) compared to silica, small thermal fluctuations can affect the optical performance especially for WDM applications. Therefore, a passive athermal solution for silicon photonic devices is required in order to reduce thermal sensitivity and power consumption. We have achieved this goal by replacing the silica top cladding with negative thermo-optic coefficient (TOC) materials. While polymers and titanium dioxide(titania) have a negative TOC, polymers can't handle high temperature processing and titania needs very tight thickness control and expensive deposition under vacuum. In this work we propose to use a sol-gel inorganic-organic hybrid material that has the benefits of both worlds. We were able to find optimum curing conditions to athermalize ring resonators by studying various sol-gel curing times and curing temperatures. Our athermal rings operate in a wide temperature range from 5C – 100C with thermal shifts below 1pm/C and low loss. Furthermore, we demonstrate that our athermal approach does not deleteriously effect critical device parameters, such as insertion loss and resonator Q factors.

10106-50, Session 11

Beyond limits of integrated photonics

Matthieu Roussey, Leila Ahmadi, Ségolène Pélisset, Markus Häyrinen, Arijit Bera, Ville Kontturi, Janne Laukkanen, Ismo Vartiainen, Seppo Honkanen, Yuri P. Svirko, Markku Kuittinen, Univ. of Eastern Finland (Finland)

We propose a novel waveguide type based on the concept of strip-loaded waveguide. A strip-loaded waveguide is composed of a thin-film slab waveguide allowing a vertical confinement of the electromagnetic field. A lower refractive index strip provides the lateral confinement by inducing a slight modification of the effective index in the slab. By using such a generic device we will demonstrate how the limits of integrated photonics can be extended, especially, in terms of propagation losses while adding complex structure on the waveguide. Since light sees only a slight variation of effective index, and not an abrupt change of material, propagation losses of the device are fully determined by the film rather than by the structuration. Different micro- and nano-structures will be presented through simulation and experimental results. We will focus especially on the study of Y-junctions, ring resonators, interferometers, and Bragg gratings. Another advantage of strip-loaded waveguides is the simplicity of fabrication. In order to fabricate the devices we employed nano-imprinting of polymer, a fabrication technique suitable for mass production. The low refractive index of the polymer allows a large panel of materials for the slab waveguide, e.g., silicon, titanium dioxide, and lithium niobate. This diversity in the choice of the materials gives to the platform the potential to operate on a wide wavelength range from UV to IR, for multiple applications in telecommunications, sensing and bio-sensing, and medical devices.

10106-51, Session 11

Near-field investigation of Bloch surface-wave-based 2D optical components

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A dielectric micro disk resonator is an important device in an integrated optical microsystem. These structures can be used for designing devices which can find wide range of applications from add-drop filters to light sources. This study aims to investigate surface wave based two dimensional (2D) disk resonators for optical integration and sensing applications.

Dielectric multilayers sustaining Bloch surface waves (BSWs) are considered as a novel platform for 2D integrated optics. Such a platform is exploited to manipulate the surface waves by patterning nano-thin 2D optical components on the top. The BSWs show potential of long propagation length (in millimeters) and field confinement, thanks to low-loss dielectric materials. These features make BSWs a good candidate for 2D integrated optics. We exploit Kretschmann configuration (phase-matching condition) for BSW excitation.

A 2D disk resonator is fabricated on the top of multilayer platform.

To study the characteristics of disk resonator in near field, we use a multi-heterodyne scanning near-field optical microscope (MH-SNOM) where evanescent surface waves are collected with subwavelength aperture probe.

For a disk radius of 100 μm, the measured Q factor is approximately 7x10^3, whereas the calculated Q factor from the finite-difference time-domain (FDTD) simulations is 2x10^4. The experiments include mainly scattering (fabrication imperfections) and leakage losses which can degrade the Q factor by an order of magnitude. The measured Q factor in this study is an order of magnitude higher than that of plasmonic based resonators. More detailed results, including 60 um disk radius, will be presented in the conference.

10106-52, Session PWed

Implementation of 3-bit binary to excess-3 code converter using Mach-Zehnder interferometer

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Excess-3 code is a non-weighted code and the primary advantage of XS-3 coding over non-biased coding is that a decimal number can be nines' complemented (for subtraction) as easily as a binary number can be ones' complemented; just invert all bits. An optical 3-bit Excess-3 code converter is demonstrated by using Mach-Zehnder Interferometers based on electro-optic effect. It is a way to represent values with a balanced number of positive and negative numbers using a prespecified number N as a biasing value.

10106-53, Session PWed

Resonant routing of optical pulses in coupled-cavity structures

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In this report, we consider 4-port structures formed by single or double circular microresonators side-coupled to strip waveguides. Using FDTD-modeling, we study spectral and temporal properties of femtosecond pulses transmitted through such integrated photonic circuits. The basic idea of our studies is to deliberately and controllably add asymmetry and losses in such circuits and to study how the reciprocal properties and connectivity of different ports depend on these parameters. Control of asymmetric optical losses was achieved by variation of the nanoscale gap separating one of the strip waveguides from such coupled-cavity structures.

We found that increasing the asymmetric losses in each incremental step, removes some general restrictions like k-vector matching for coupling between microresonator and waveguide, and as a result, it is not only the nonreciprocity that can be presented in the system, but also we can control the path of different modes, and interestingly direction of connectivity between ports become frequency dependent. This opens

principle possibilities to design a structure with wavelength demultiplexing functionality, and we demonstrated bigger that 10 dB path ratio difference for resonant routing of optical pulses in such structures.

We also showed that the level of transmitted pulses can be restored in such structures by introducing a gain in such a way that the nonreciprocal optical transport and frequency-dependent routing properties established for passive structures would be still present in the optical properties of corresponding active structures.

10106-54, Session PWed

Characterization of glass planar waveguides prepared by copper ion exchange method

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Ion exchange technique is an important method for fabricating glass waveguide devices. Compared with the traditional Ag+-Na+ and K+-Na+ ion exchange methods, copper-alkali metal ion exchange is an interested and valuable technique for fabricating glass waveguides because the doped copper ions in glass wafers not only results in refractive index change for making waveguides, but also produces blue-green luminescence. Obviously, it was possible that both passive and active waveguide devices could be integrated into one glass substrate by copper ion exchange technique. Therefore, the research for the copper ion-exchanged glass waveguides will be very good application prospects.

It is well known that the copper state is very sensitive to the glass substrate composition as well as to the doping route, making difficult to control the copper state. In most cases, there are different copper oxidation states in the glass matrix after copper ion-exchanged, namely Cu0, Cu+ and Cu2+, possibly forming also either Cu or Cu2O clusters. Thus, optical property in the waveguides is complex and interesting. In this work, we fabricated planar waveguides on glass substrates using thermal ion exchange technique. Then, the waveguides were annealed in the air 1 hour at different temperatures. The properties of the waveguides and their blue-green luminescence were studied. It was observed that the refractive index profiles and the blue-green luminescence of the waveguides were strongly influenced by prepared process and annealed processes.

10106-55, Session PWed

Design and simulation of 20-channel 50-GHz Si3N4-based arrayed waveguide grating applying AWG-parameters tool

Dana Seyringer, FH Vorarlberg (Austria); Catalina Burtscher, Czech Technical Univ. in Prague (Czech Republic) and FH Vorarlberg (Austria); Stefan Partel, Johannes P Edlinger, FH Vorarlberg (Austria); Alejandro Maese-Novo, Paul Muellner, Rainer Hainberger, AIT Austrian Institute of Technology GmbH (Austria); Jochen Kraft, Guenther Koppitsch, Gerald Meinhardt, ams AG (Austria)

We present the various designs of 20-channel, 50-GHz Si3N4 based AWG applying our proprietary AWG-Parameters tool. The designed AWGs were simulated by two commercial photonics tools and the achieved transmission characteristics were evaluated. The AWGs were designed for TM-polarized light with a central wavelength of 850 nm in the framework of the COHESION project and they will later be used in a photonic integrated circuit dedicated to medical diagnostic imaging applications.

AWG DESIGN

The AWG design begins with the calculation of its dimensions, which are essential to create the AWG layout. The dimensions are given by the geometrical parameters, as:

• minimum waveguide separation between the PA waveguides (parameter dd),

• minimum waveguide separation between the input/output waveguides (parameter dx),

• length of the star coupler (parameter Lf), and

• optical path length difference between adjacent waveguides in the phased array (parameter dL).

As there is a strong correlation between the dimensions of the AWG structure and its performance (defined by the transmission parameters, i.e. insertion loss, insertion loss uniformity, channel crosstalk, etc.), the AWG geometrical parameters have to be calculated with a high degree of precision. In the previous work we studied the influence of the parameter dd on the insertion loss and found the appropriate minimum waveguide separation between the PA waveguides in order to minimize insertion losses. In this work we will present the influence of the parameter dx on the channel crosstalk and also on the size of the AWG structure those should be kept both as small as possible.

10106-56, Session PWed

New waveguide shape for low-loss and high-uniformity y-branch optical splitter

Catalina Burtscher, Czech Technical Univ. in Prague (Czech Republic) and FH Vorarlberg (Austria); Dana Seyringer, FH Vorarlberg (Austria); Michal Lucki, L. Kohler, Czech Technical Univ. in Prague (Czech Republic)

Y-branch splitters are the key components in FTTX networks because they are polarization and wavelength independent, i.e. one device can be used to split optical signals in the whole operating wavelength window. However, the processing of branching points where two waveguides start to separate, is technologically very difficult leading to an asymmetric splitting ratio of the split power over all the output waveguides. Although it does not have a significant influence on the splitting properties of low channel 1xN splitters (N<16) it becomes a dominant factor in the splitting of 1x16, 1x32 or 1x64 optical signals causing a huge rise in asymmetric splitting ratio. Furthermore, such splitters are rather large compared to other splitting approaches, increasing strongly the fabrication costs. In this paper a new Y-branch shape was proposed for 1x32 Y-branch splitter leading to a splitter design with the strong improvement of its splitting properties.

To supress optical losses in the “standard” Y-branch splitter the “new” branch shape was developed to make it applicable for high channel Y-branch optical splitters. The maximum background noise of “new shape” Y-branch splitter, is improved nearly by 4 dB, namely from -46.31 dB to -42.6 dB only. The non-uniformity of the new shape 1x32 Y-branch splitter is reduced by more than one third of the non-uniformity of the standard 1x32 Y-branch splitter namely from 3.65 dB to 2.2 dB. Also the insertion loss, IL was improved nearly by 1 dB, i.e. from -18.67 dB to -17.765 dB.

10106-57, Session PWed

Polymer planar waveguide Bragg gratings: fabrication, characterization, and sensing applications

Manuel Rosenberger, Steffen Hessler, Hochschule Aschaffenburg (Germany); Hendrikje Pauer, Karlsruher Institut für Technologie (Germany); Maiko Girschikofsky, Gian-Luca Roth, Benedikt Adelmann, Hochschule Aschaffenburg (Germany); Heinz Wörn, Karlsruher Institut für Technologie (Germany); Bernhard Schmauss, Friedrich-

Alexander-Univ. Erlangen-Nürnberg (Germany); Ralf Hellmann, Hochschule Aschaffenburg (Germany)

Polymers are gaining increasing interest in optical technologies especially as raw material for polymer sensors. Whereas these sensors are mainly based upon polymer optical fibers, planar structures exhibit some distinctive advantages which are worth exploiting. In this contribution, we give a comprehensive overview of the fabrication, characterization, and application of integrated planar waveguide Bragg gratings (PPBGs) in cyclo-olefin copolymers (COC). Starting with the measurement of the refractive index depth profile of integrated UV-written structures in COC by phase shifting Mach Zehnder Interferometry, we analyze the light propagation using numerical simulations. Furthermore, we show the rapid fabrication of humidity insensitive polymer waveguide Bragg gratings in cyclo-olefin copolymers and discuss the influence of the UV-dosage onto the spectral characteristics, the transmission behavior of the waveguide, and the attenuation of the integrated structures. Based on these measurements we exemplify that our Bragg gratings exhibit a reflectivity of over 99 % and are highly suitable for sensing applications. With regard to a negligible affinity to absorb water and in conjunction with high temperature stability these polymer devices are ideal for mechanical deformation sensing. Since planar structures are not limited to tensile but can also be applied for measuring compressive strain, we manufacture different functional devices and corroborate their applicability as optical sensors. Exemplarily, we highlight a temperature referenced PPBG sensor written into femtosecond-laser cut tensile test geometry for tensile and compressive strain sensing. Furthermore, a flexible polymer planar shape sensor is presented.

10106-58, Session PWed

Mode coupling for wavelength filter consisting of a mode conversion grating and a mode sorting waveguide

Tae-Hyun Park, Guanghao Huang, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

A tunable wavelength filters is necessary in order to filter specific wavelength in the WDM signals transmitted to subscribers in the WDM optical communication system. The wavelength filter based on polymer Bragg reflector is attracting attention with the advantage of a simple structure and a wide tuning range. The reflected light returns to the input port in an ordinary Bragg reflector. By using the tilted Bragg grating and asymmetric Y-branch, reflected light can extracted to another port. In this work, we propose and design asymmetric Y-branch and tilted Bragg grating for optimizing the mode coupling efficiency. The asymmetric Y-branch exhibits good mode sorting efficiency and tilted Bragg reflector operates as a mode converter. The wavelength filters using the polymer material were fabricated, which were measured and compared with the design value. The crosstalk in the mode sorting asymmetric Y-branch was less than -20 dB. The error of tilt angle was less than 0.1°. The proposed device provides large manufacturing tolerances, which is necessary for the high-yield mass production.

10106-59, Session PWed

Optical voltage sensors based on polymer waveguide integrated optics

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An optical voltage sensor offers significant advantages over their electrical counterparts in many aspects, especially in measuring high electric fields. We proposed an optical voltage sensor which is consist of a sensing probe by using $LiTaO_3$ crystal and photonic integrated circuit (PIC) based on polymer waveguide devices for configuring polarization rotated reflection interferometer (PRRI). When two orthogonal polarized light is passing through the crystal which is applied voltage on both sides, the phase retardation is occurred by electro-optic effect. The phase retardation is analyzed by PIC with PRRI configuration. Conventional Interferometric sensors such as Mach-Zehnder interferometer normally require bias feedback control system for maintaining the operating point to get the highest sensitivity. As the feedback system makes the sensor complicate and need more cost, we proposed a bias-free operable system by consisting the PIC with 2 x 4 MMI coupler, HWP film, and power splitter. The output interference signals from 2 x 4 MMI coupler show 90 deg phase difference to another one which can be used for quadrature demodulation technique. As the result of the technique, the final signal shows constant output even the bias is drifting over 2pi. In the voltage measurement experiment, the output sensor signal was linearly proportional to the applied voltage about 4kVpp 60Hz sinusoidal signal.

10106-60, Session PWed

Integrated optic current sensors operating without active quadrature bias feedback control

Sang-Guk Kim, Woo-Sung Chu, Sung-Moon Kim, U-Jeong Chu, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

Optical current sensors are indispensable devices for the accurate monitoring of large electrical currents in environments suffering from severe electromagnetic interference. The optical current sensor based on polarization rotated reflection interferometry is implemented by incorporating polymeric photonic integrated circuits (ICs). To reduce a temperature dependence of sensor head unit, a QWP was made of photonic crystal polarization maintaining fiber (PCPMF) instead of panda type PMF and sensing fiber coil was made of high birefringence spun fiber (HBSF) instead of annealed SMF. Interferometric sensors normally require bias feedback control for maintaining the operating point. However, this makes the sensor complicated and expensive. In order to resolve this constraint of feedback control, a quadrature phase shifted transfer function was utilized along with the original interference signal in this work. Based on the polymeric optical waveguides technology, the two operating transfer functions were obtained by integrating two kinds of waveplates, waveguide polarizers, and waveguide branches. The phase difference of two transfer functions was shown 90°. In the experiment of current measurement, the optical signal exactly followed the 4 kArms, 60 Hz sinusoidal waveform source current. Using passive quadrature demodulation, we demonstrate that the sensor could maintain the output signal regardless of the drift in the operating bias point. Photonic ICs reduce the complexity of the interferometry and enable mass-production of low-cost high-performance electric field sensors.

10106-61, Session PWed

Design of waveguide integrated uni-traveling carrier photodiode with low-polarization dependent loss

Young-Ho Ko, Joong-Seon Choe, Won-Seok Han, Jong-Hoi Kim, Electronics and Telecommunications Research Institute (Korea, Republic of)

The drastic increase of data traffic has required high-speed components of optical communication including laser diodes, modulator and photodiodes (PDs). To realize high-speed PDs, various kinds of structure have been introduced and studied. Compared to a PIN PD, the uni-traveling carrier (UTC) PD, where the light absorption is occurred in p-type region, can have high operation speed with high power due to reducing the space-charge effect. Compared to the surface illuminated PD, the evanescently-coupled

waveguide (WG) PD has advantages of high-speed operation as well as high responsivity. Although complicated device design for light coupling efficiency between WG and absorption layer compared to PIN PD, the WG integrated UTC PD can have both advantages of WG and UTC structures.

The coherent receiver for coherent optical communication is normally composed of the optical hybrid and balanced photodetector arrays. For high coupling efficiency between WG PD arrays and planar lightwave circuit, the spot-size converter (SSC) is introduced. However, semiconductor-based SSC and WG cannot normally have symmetric cross-section between lateral and vertical direction. So they have different propagation behavior between TE- and TM- polarization, resulting in polarization dependent loss (PDL). Therefore, reducing the PDL is critical issue in SSC-integrated WG PD as well as increasing the responsivity.

In this study, we suggest and design the modified UTC PD for WG integrated UTC PD, and we successfully realized low PDL and high responsivity by adopting the laterally-tapered SSC. The SSC was designed as the diluted WG, dual lateral taper structure, and modified UTC PD. The epitaxial layers of InxGa1-xAsyP1-y/InP, InxGa1-xAsyP1-y, were adopted as the diluted WG, dual tapers, respectively. While the normal UTC PD has p-type absorption layer and undoped collection layer, we could reduce the collection layer thickness to 150 nm by dividing the absorption layer as p-InGaAs (150 nm) and undoped-InGaAs (280 nm) for high light coupling efficiency, named as modified UTC PD. The shape and thickness of each structure were determined through the simulation of 3D finite-difference beam propagation method. Despite of the difficult light coupling of UTC structure, it was estimated that the modified UTC PD has responsivity and PDL of 0.66 A/W and 0.3 dB, respectively. The WG integrated UTC PD was expected to have large bandwidth with high responsivity.

10106-62, Session PWed

Design and fabrication of photonic quasi-crystal light coupler and splitter on low refractive index material

Jingxing Shi, Univ. of Southampton (United Kingdom); Michael E. Pollard, The Univ. of New South Wales (Australia); Martin D. B. Charlton, Univ. of Southampton (United Kingdom)

Coupling light and splitting power are usually achieved by grating coupler and MMI or Y-splitters.To date, there has been few attempts to achieve combing these two functions into one device in order to couple light efficiently from an excitation Laser into the Planar Light Circuit without tight constraints on alignment accuracy and bandwidth.

In this paper, we demonstrate a new multi-channel coupler / splitter device based on Photonic Quasi-crystal (PQC). This provides a compact and efficient alternative to the conventional grating coupler + integrated optical waveguide splitter. A 12-fold symmetric PQC gives 12 provides 12 channel splitting as well as near-vertical coupling. Directional beam splitting properties can be determined by conventional Ewald sphere construction. Channel splitting can be extended to arbitrary numbers of channels by changing the Stamfli inflation protocol which constructs the PQC lattice. Wavelength can be tuned by adjusting the lattice constant. Test devices are fabricated on SION/SIO2 substrate. The lattice constant is optimised in order to achieve good phase matching between incident near vertical Laser beam and PC Bloch modes. Normal incidence coupling as well as 12 channel splitting is demonstrated experimentally.

10106-63, Session PWed

Reactive mesogen waveguide polarization splitters based on total internal reflection

Guanghao Huang, Jin-Soo Shin, Tae-Hyun Park, Woo-Sung Chu, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

To deal with the daily growing data traffic capacity over the internet, the need for quantum encrypted communication arises. In quantum communication, for detecting a specific polarization state (such as orthogonal Bell state polarization) used for encryption, various optical components including polarization splitter are necessary. In this work, a reactive mesogen (RM) waveguide polarization splitter based on total internal reflection with a high splitting ratio is proposed and demonstrated. RM is a rod-like liquid crystalline material with crosslinking end groups. It is useful to form a thin film with a large birefringence by coating and UV curing the liquid oligomer. RM has refractive indices of 1.6457 and 1.5205 for TE and TM polarizations, respectively. A waveguide polarization splitter incorporating RM could be fabricated through a photo-lithography process. The device consists of a mode expander for reducing the spatial distribution of the guided mode and an interface with a large birefringence. The mode expander was designed by the effective index method and the 2-dimensional beam propagation method (BPM). On the TIR interface formed by the highly birefringent RM material, TE polarization was internally reflected, while TM polarization passed through. According to the various simulation results, optimum device structure was found and fabricated. Fabricated polarization splitter with an incident angle of 76° exhibits a high polarization splitting ratio and a crosstalk of less than -30 dB.

10106-64, Session PWed

Photonic nanojet properties of dielectric micro-cylinders

Arash Darafsheh, Douglas Bollinger, Univ. of Pennsylvania (United States)

Photonic nanojets are intense sharply focused photon beams formed by dielectric microspheres and microcylinders. In this work, by means of finite-difference time-domain (FDTD) numerical simulation, we studied the nanojet properties of dielectric microcylinders over a wide range of diameters (2?-20?) and refractive indices (1.5-2.1), where ? is the wavelength of light. We studied in detail the nanojet size, intensity, and focal length as a function of size and refractive index of the particle. Our results will inform on the design of novel optical devices, such as microparticle-embedded microscope slides.

10106-65, Session PWed

Visual sensing with plasmonic nanoporous structure

Yeonhong Kim, Kyuyoung Bae, Kyoungsik Kim, Yonsei Univ. (Korea, Republic of)

Change in solution sample's refractive index can be measured by optical sensor, and its capability leads the continuous development on this topic. Following this trend, we applied a plasmon-cavity coupled nano-scale template of anodic aluminium oxide (AAO) to demonstrate a refractive index sensor that covers relatively large area. The coupled mode of the interference by Fabry-Perot microcavity and metallic nano interfaces enables us to accomplish an enhancement of the figure-of merit and sensitivity. As AAO pores and analytes interact each other and the mode confinement increases, highly modulated reflection spectra is shown, and this result leads increment in refractive index sensitivity and a figure-of-merit value. Moreover, our sensor can simultaneously measure the

refractometric and visual sensing with spectrometer and conventional camera. A progress in visual sensing performance has been achieved using infiltrated analytes that induces the dramatic color change. Our approach simplified the procedures in detecting multiple analytes and result with cost-effective and highly sensitive optical sensor.

10106-66, Session PWed

Laws of Nature for forces: the discovery of Cubal laws and constant

Arjun Krishnappa, Univ. of Dayton (United States)

Calculating the net optical force (Gaussian beam) on molecules that are enclosed by a sphere, requires rigorous mathematical steps and consumes more time. Also it is complex to compute the total force on molecules that are on a sphere. As a result the easy approximate way of calculating the net force is by assuming the sphere as a cube, which reduces the complexity. One disadvantage with this method is that the net force is not the actual force, but the approximated force. Interestingly, this research has found a universal constant that relates the sphere and cube called "Cubal Constant." Based on this constant, two laws have been proposed: Cubal Volume Law and Cubal Surface Law. Cubal Volume Law can be used for determining the net force on molecules in the sphere, whereas Cubal Surface Law is used to compute the force on molecules which are on the sphere. Using these two laws, the exact net force on molecules which are in/on the sphere can be calculated by just calculating the force on molecules which are in/on the cube. These two laws can be treated as force laws, so this can be extended to many other applications that involve forces. The constant and laws are theoretically and experimentally verified.

10106-68, Session PWed

Simulation of 20-channel, 50-GHz, Si3N4-based arrayed waveguide grating applying three different photonics tools

Lenka Gajdo?ová, Dana Seyringer, FH Vorarlberg (Austria)

We present the design and simulation of 20-channel, 50 GHz Si_3N_4 based AWG applying our proprietary AWG-Parameters tool. This AWG was designed for TM-polarized light with an AWG central wavelength of 850 nm. It was later simulated using three different commercial photonic tools, namely PHASAR from Optiwave Systems Inc., APSS from Apollo Photonics Inc. and RSoft from Synopsys Inc. For this purpose we created identical waveguide structures and identical AWG layouts in these tools and performed BPM simulations. For the simulations the same calculation conditions were used. The output of all simulations are the transmission characteristics. They were used to calculate the transmission parameters describing the optical properties of the simulated AWGs. These parameters were summarized and compared to select the most suitable photonic tool. Although the design procedures are very similar, the simulation results can vary from one tool to another. From achieved transmission characteristics it is evident that the simulation performed by the Optiwave tool varies from simulations from Apollo Photonics and RSoft tools. On the other hand, the characteristics from Apollo Photonics and RSoft tools are similar to each other. Nevertheless, the transmission parameters calculated from all characteristics feature very good correlation between each other and are comparable to the designed parameters in AWG-Parameters tool.

10106-69, Session PWed

On-chip integrated free-electron light source

Fang Liu, Long Xiao, Yu Ye, Mengxuan Wang, Yidong Huang, Tsinghua Univ. (China)

To generate Cherenkov radiation (CR) in natural medium, the electron energy threshold is higher than hundreds of keV. Even though various approaches were adopted, the high-energy electrons as high as tens of keV is still required in experiment. Here we proposed to eliminate the threshold of electron energy to generate CR with the help of hyperbolic metamaterial (HMM). The analytical and simulation results indicate that, even though electron energy is lower than 0.1keV, the CR could be obtained in HMM in a visible and near-infrared frequency region. Further, the on-chip integrated threshold-less CR source, consisted with a planar electron emitter, Au-SiO_2 multilayers HMM, and periodic metal nano-slits, has been realized. It is demonstrated that, with low-energy electrons (0.25-1.4keV), the CR is generated covering ?0=500~900nm. The electron energy generating CR experimentally is two~three orders of magnitude lower than that in natural media and artificial structures. As we know, this is the first on-chip integrated free electron light source benefiting from the threshold-less CR. Although less than 1% of the light energy could be coupled to free space, the total output light power still reaches 200nW, which is two orders of magnitude higher than free electron light source by using other nanostructures. This work provides a way to realize threshold-less CR, opens up the possibility of exploring high performance on-chip integrated free electron light source and optoelectronic devices, and offers the platform to study the interaction of flying electrons with nanostructures on chip.

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10107-1, Session 1

Integrated Bragg grating filters and modulators in SOI *(Invited Paper)*

Sophie La Rochelle, Univ. Laval (Canada); Alexandre D. Simard, Ciena Corp. (Canada)

Compared to Mach-Zehnder lattice filters or coupled micro-ring resonators, integrated Bragg grating (IBG) filters are a preferred solution when a precisely tailored spectral response is desired. IBGs can achieve custom shaping of both amplitude and phase providing, for example, narrow linewidth filters with large FSR or passband filters with well-controlled dispersion. Furthermore, data transmission can be obtained by modulating the sharp spectral responses of IBGs.

The design of high performance IBGs in SOI must include strategies to mitigate current limitations of the CMOS compatible fabrication process: 1) first order gratings require feature sizes at the limit of current UV lithography, and 2) the large index step and field overlap at the core-cladding boundary of singlemode silicon waveguides results in relatively large coupling coefficients, even for small sidewall corrugations, which is an important constraint for implementation of apodization functions. We present an approach to IBG filter design that includes measurement and calibration of the coupling coefficients, and propose apodization by varying the phase between the two sidewall gratings. We demonstrate a narrow bandwidth (<20 GHz) filter, as well as dispersion-less and chirped bandpass filters.

Combining a phase-shifted IBG with pn-junctions operated in carrier depletion mode, we demonstrate 50 Gbit/s OOK modulation. We propose a dynamic model that could be used to further optimize the grating parameters of IBG modulators maximizing the optical modulation amplitude.

In conclusion, with adequate design and optimization, the performance of IBG filters and modulators make them an attractive solution for data communication applications.

10107-2, Session 1

Subwavelength metamaterial engineering for silicon photonics *(Invited Paper)*

Robert Halir, Alejandro Ortega-Moñux, Univ. de Málaga (Spain); Jordi Soler-Penadés, Optoelectronics Research Ctr., Univ. of Southampton (United Kingdom); José M. Luque-González, Jose-Dario Sarmiento-Merenguel, Alejandro Sánchez-Postigo, Juan Gonzalo Wangüemert-Pérez, Univ. de Málaga (Spain); Jens H. Schmid, Dan-Xia Xu, Siegfried Janz, Jean Lapointe, National Research Council Canada (Canada); Íñigo Molina-Fernández, Univ. de Málaga (Spain); Milos Nedeljkovic, Goran Z. Mashanovich, Univ. of Southampton (United Kingdom); Pavel Cheben, National Research Council Canada (Canada)

Waveguides structured at the subwavelength scale frustrate diffraction and behave as optical metamaterials with controllable refractive index and dispersion. These structures have found widespread applications in silicon photonics, ranging from sub-decibel efficiency fibre-chip couplers to spectrometers and polarization rotators. Here, we briefly describe the design foundations for sub-wavelength waveguide devices, both in terms of analytic effective medium approximations, as well as through rigorous Floch-Bloquet mode simulation. We then focus on two novel structures that exemplify the use of subwavelength waveguides: mid-infrared waveguides and ultra-broadband beamsplitters in the near-infrared. Silicon is fully transparent up to wavelengths of 8μm, but the buried oxide (SiO2) layer that optically insulates the waveguide from the substrate starts to become lossy around 4μm. Using waveguides with a subwavelength lateral cladding, which can be defined in a single etch step, the buried oxide layer can be removed by passing hydrofluoric acid through the sub-wavelength holes. This results in suspended waveguides that are mechanically supported by the lateral subwavelength structure and exhibit propagation losses below 1dB/cm. On the other hand, integrated beamsplitters are usually implemented with multi-mode interference couplers. With typical bandwidths of 50nm to 100nm in the near-infrared, these devices are broadband compared to other alternatives such as directional couplers. However, using subwavelength structures to engineer the dispersion of the multimode waveguide, this bandwidth can be further extended, with recent measurements showing operation over a range of more than 200nm at telecom wavelengths.

10107-3, Session 1

Nanophotonics technology and applications *(Invited Paper)*

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

The integration of a photonic information processing system onto a single chip requires great research effort toward engineering metamaterials for miniaturization of the optical devices and circuits. We discuss nanoscale engineered optical nonlinearities for modulation, switching and wave mixing of optical fields, and metal-dielectric-semiconductor nanostructures and compositions to construct nanoemitters for chip-scale integration.

10107-4, Session 2

Trends in heteroepitaxy of III-Vs on silicon for photonic and photovoltaic applications *(Invited Paper)*

Sebastian Lourdudoss, KTH Royal Institute of Technology (Sweden); Carl Junesand, KTH Royal Institute of Technology (Sweden) and Epiclarus AB (Sweden); Himanshu Kataria, KTH Royal Institute of Technology (Sweden) and IRnova AB (Sweden); Wondwosen Metaferia, KTH Royal Institute of Technology (Sweden) and Lund Univ. (Sweden); Giriprasanth Omanakuttan, Yan-Ting Sun, KTH Royal Institute of Technology (Sweden); Fredrik Olsson, KTH Royal Institute of Technology (Sweden) and Höganäs AB (Sweden); Zhechao Wang, KTH Royal Institute of Technology (Sweden) and Univ. Gent (Belgium)

We present and compare the existing methods of heteroepitaxy of III-Vs on silicon and their trends. We focus on the epitaxial lateral overgrowth (ELOG) method as a means of achieving good quality III-Vs on silicon. Initially conducted primarily by near-equilibrium epitaxial methods such as liquid phase epitaxy and hydride vapour phase epitaxy, nowadays ELOG is being carried out even by non-equilibrium methods such as metal organic vapour phase epitaxy. In the ELOG method, the intermediate defective seed and the mask layers still exist between the laterally grown purer III-V layer and silicon. In a modified ELOG method called corrugated epitaxial lateral overgrowth (CELOG) method, it is possible to obtain direct interface between the III-V layer and silicon. In this presentation we exemplify some recent results obtained by these techniques. We assess the potentials of

these methods along with the other exiting methods for realizing truly monolithic photonic integration on silicon and III-V/Si heterojunction solar cells.

10107-6, Session 2

Efficient plasmonic integrated circuits *(Invited Paper)*

Amr S. Helmy, Yiwen Su, PoHan Chang, Charles Lin, Univ. of Toronto (Canada)

Recent advances in nano-photonics have significantly increased our ability to realize novel nano-scale waveguides for light confinement. In this talk I plan to discuss a class of nanoscale waveguides that address unmet performance demands for applications in telecommunications, where the elements of efficient transceivers will be discussed.

The talk describes an architecture/design methodology that provides optimal utilization of 2D materials eliminating existing trade-offs associated with field confinement and propagation losses. It is not a conventional theoretical device design paper. The following unique features distinguish this work:

• A solution to elimnates the extinction ratio-insertion loss trade-off that commonly limits the performance of optical modulators integrated with 2D materials.

• The first reported flexible biasing strategy that enables a single waveguide element to be dynamically reconfigured to support amplitude, phase or coherent quadrature-amplitude-modulation.

• Device performance that marks departure from existing modulator designs, offering compact device footprint (~100 nm for amplitude modulation), sub-fJ power consumption, and THz operating bandwidth.

• Athermal behavior and strong fabrication tolerance that are afforded by the non-resonant nature of the proposed modulation scheme.

• Versatile waveguide design strategy that has no material restrictions and thus suitable for diverse material platforms and fabrication processes.

Overall, the proposed architecture and the associated design methodology will serve as a blueprint for implementing integrated optical devices for which true maximal wave-matter interaction can be achieved between the few-layer materials and the guided waveguide structures.

10107-7, Session 2

Nanoscale transfer printing for heterogeneous device integration *(Invited Paper)*

Antonio Hurtado, Benoit J. E. Guilhabert, Michael J. Strain, Nicolas Laurand, Univ. of Strathclyde (United Kingdom); Chennupati Jagadish, The Australian National Univ. (Australia); Martin D. Dawson, Univ. of Strathclyde (United Kingdom)

We present a novel nanoscale transfer printing (TP) technology which combines a customized nanolithography system with bespoke elastomeric ?-stamps to controllably pick and place diverse semiconductor structures, e.g. nanowires (NWs), Light Emitting Diodes (LEDs) and thin films, onto targeted locations on heterogeneous material surfaces (e.g. polymers, metals, silica, diamond). Notably, our technique allows the parallel printing of semiconductor structures of different materials onto a large area (of 10cm x 10cm) whilst simultaneously yielding sub-micrometric positioning control (down to below 100nm) and low printing time (~20s per print step). In the talk, we will present a variety of hybrid integrated devices fabricated with our TP technique. Emphasis will be given to our recent work using Gallium Nitride (GaN) LEDs and Indium Phosphide (InP) NW lasers as building blocks. Using TP protocols, GaN LEDs fabricated from GaN-on-Si have been integrated onto polymer and thin glass surfaces and onto diamond substrates for mechanically flexible optoelectronic devices and effective device heat management respectively. Additionally, ultra-small InP NW lasers (~5?m long and ~500nm diameter) have been integrated onto multiple heterogeneous substrates, including mechanically flexible (polymers), transparent (silica) and metallic (gold) surfaces. Furthermore, complex spatial patterns with micrometric dimensions have been defined with these nanolasers acting as localised emitters. Finally, we will also introduce our very recent results demonstrating the coupling of InP NW lasers with planar waveguide technology as a back-end hybrid integration technique.

10107-8, Session 2

Rapid virtual prototyping of complex photonic integrated circuits using layout-aware schematic-driven design methodology

Sergei Mingaleev, VPI Development Ctr. (Belarus); André Richter, VPIphotonics GmbH (Germany); Eugene Sokolov, Stanislau Savitzki, VPI Development Ctr. (Belarus); Andrzej Polatynski, VPIphotonics GmbH (Germany); Jim Farina, VPIphotonics (United States); Igor Koltchanov, VPIphotonics GmbH (Germany)

We present the advantages of our recently developed versatile simulation framework enabling the schematic-driven and layout-aware design of optoelectronic and photonic integrated circuits (PICs). It supports hierarchical circuit designs and advanced parameter scripting, realizing a fast and user-friendly design flow for large-scale PICs comprising passive and active building blocks (BBs). Multidimensional parameter sweep and circuit optimization, sensitivity and yield analysis can be set up automatically helping to increase the productivity of PIC designers.

We show how the seamless interaction of circuit simulation with photonic layout design tools (such as OptoDesigner by PhoeniX Software, IPKISS by Luceda Photonics) allows to specify and utilize directly the physical locations and orientations of BBs of standardized process design kits (PDKs) on the final layout. In application to integrated photonics (and in contrast to integrated electronics), this interaction is of eminent importance as interference of optical waves are non-negligible. Consequently the physical lengths of optical connectors cannot be ignored when analyzing and optimizing the overall PIC performance. We demonstrate how to combine graphical schematic capture and automated waveguide routing by using smart adaptive optical connectors linking sub-circuits with fixed locations and possibly predefined layout.

We discuss by means of several typical design applications realized using Si, InP and polymer photonics technologies how an optimized design flow can speed-up the virtual prototyping of complex photonic integrated circuits and optoelectronic applications.

10107-9, Session 3

Ion implantation in silicon to facilitate testing of photonic circuits *(Invited Paper)*

Graham T. Reed, Milan M. Milosevic, Xia Chen, David J. Thomson, Univ. of Southampton (United Kingdom)

In recent years we have presented results on the development of erasable gratings in silicon to facilitate wafer scale testing of silicon photonics circuits. These gratings are formed by amorphising selected areas of silicon by utilising ion implantation of germanium. Similar technology can be employed to develop alternative testing strategies based on different device designs, as well as for trimming of integrated photonic components. In this paper we discuss a series of devices that can be fabricated using ion implantation of Germanium (or indeed, other ions) into silicon.

Ion implantation into silicon causes radiation damage. If a sufficient dose is implanted, complete amorphisation can result in a local part of the device. Amorphous silicon has a refractive index that is significantly different higher than that of crystalline silicon (~10-1), and can therefore form the basis of multiple optical devices. We have carried out experiments to demonstrate the principle of implementation of a series of devices for wafers scale testing. In addition we have implemented the ion implantation based refractive index change in a selection of integrated photonic devices, although application to any optical device is possible, particularly resonant structures. Therefore this reversible refractive index can be selectively removed to tune the operating wavelength, by selective local laser annealing. We discuss these results in the context of both wafer scale testing and active device trimming.

10107-10, Session 3

Active plasmonic-dielectric integrated devices on silicon platform based on metal-edge enhanced mode confinement *(Invited Paper)*

Seng-Tiong Ho, Michael Hsieh, Qiang Bai, Northwestern Univ. (United States); Yingyan Huang, OptoNet Inc. (United States); Yongming Tu, OptoNet, Inc. (United States); Leonides E. Ocola, Argonne National Lab. (United States); Chenguang Yuan, Northwestern Univ. (United States)

The realization of optical gain in metal-dielectric-metal (MDM) nanoscale-waveguide is of interest to overcome optical loss. This can be achieved with use of III-V semiconductor as the dielectric material to provide the optical gain. For example, an InP-based quantum well active layer can be fabricated on silicon (SOI) substrate using wafer bonding technique. The active layer can then be etched down vertically to form a ~100nm-wide dielectric structure. When coated with metal, it will form a MSM (metal-semiconductor-metal) waveguide capable of optical gain. The coated metal will form L-shape edges at the bottom of the structure.

We investigate the vertical mode size and gain-medium field overlapping factor of such MSM waveguide at 1550nm wavelength range for which a high-refractive-index waveguiding core structure is used to confine the mode vertically (horizontally the mode confinement is via the MSM waveguide). We find that when the waveguide core structure is placed at near the L-shape metal edges, the vertical mode size is minimal and the field overlapping factor with quantum wells in the waveguide core is over 100% (two-time) higher than when the core is at way above the metal edges. This is due to enhanced mode confinement caused by the metal edges because of the strong mode-confining effect of metal edges.

In conclusion, we show that a significantly higher optical gain can be achieved via placing the active dielectric waveguide core near the bottom metal edges, which will give the optimal active layer structure for integrated active plasmonic-dielectric devices based on MDM waveguides.

10107-11, Session 3

New directions for stimulated Brillouin scattering in integrated circuits *(Invited Paper)*

Raphaël Van Laer, Stanford Univ. (United States) and Univ. Gent (Belgium); Christopher J. Sarabalis, Stanford Univ. (United States); Paul Tiebot, Dries Van Thourhout, Univ. Gent (Belgium); Amir H. Safavi-Naeini, Stanford Univ. (United States); Roel G. Baets, Univ. Gent (Belgium)

We present an overview of and recent advances on photon-phonon interaction in integrated circuits. First we discuss the observation of gain coefficients up to 10000/(Wm) in nanoscale silicon waveguides. Next we describe the first measurement of thermally-seeded Brillouin scattering in these waveguides. The waveguides consist of a series of suspended silicon nanowires, supported by thin silicon socket layers. The thermal measurement simplifies set-ups previously used to extract stimulated Brillouin resonances from silicon nanowires. Finally we explore new directions for these systems. Thermally seeded interactions between propagating photons and phonons may permit robust temperature measurements on a silicon chip. Traveling-wave photon-phonon coupling is on the verge of entering the quantum regime, enabling studies of non-local effects – such as spatial strong coupling – absent in traditional cavity quantum optomechanics.

10107-12, Session 4

Multi-functional photonic crystal sensors enabled by biological silica *(Invited Paper)*

Alan X. Wang, Oregon State Univ. (United States)

Diatoms are microalgae found in every habitat where water is present. They produce 40% of the ocean's yearly production of organic carbon and 20% of the oxygen that we breathe. Their abundance and wide distribution make them ideal materials for a wide range of applications as living organisms. In our previous work, we have demonstrated that diatom biosilica with self-assembled silver nanoparticles (Ag NPs) can be used as ultra-sensitive, low-cost substrates for surface-enhanced Raman scattering (SERS) sensing. The enhancement comes from the photonic crystal enhancement of diatom frustules that could improve the hot-spots of Ag NPs. In this work, we report the unique micro-fluidic flow, analyte concentration effect, and thin layer chromatography (TLC) on diatom biosilica, which enables selection, separation, detection, and analysis of complex chemical and biological samples. Particularly, we show that the microscopic fluidic flow induced by the evaporation of liquid droplet can concentrate the analyte and achieve label-free sensing of single molecule detection of R6G and label-free sensing of 4.5?10-17g trinitrotoluene (TNT) from only 200 nano-liter solution. We also demonstrated a facile method for instant on-site separation and detection of analytes by TLC in tandem with SERS spectroscopy using high density diatom thin film. This lab-on-chip technology has been successfully applied for label-free detection of polycyclic aromatic hydrocarbons from human plasma and histamine from salmon fish. Our research suggests that such cost-effective, multi-functional photonic crystal sensors enabled by diatom biosilica opens a new route for lab-on-chip systems and possess significant engineering potentials for chemical and biological sensing.

10107-13, Session 4

Nanophotonic cavity sensing for oil and water

Huub W. Salemink, Radboud Univ. Nijmegen (Netherlands); Yazhao Liu, Technische Univ. Delft (Netherlands)

The proof of concept for a photonic cavity sensor for oil, water and gas detection is reported. The optical design employs an optimized photonic crystal cavity with fluidic infiltration of gas, water or (reservoir) oils. The 3D design and simulation is discussed, followed by the nanofabrication in standard silicon on insulator wafers (SoI). Using an optofluidic cicuit with PDMS channels, the fluid flow to the photonic cavity is controlled with syringe pumps. The variations in dielectric value (refractive index) change with the involved media result in a shift of the cavity resonant wavelength. For fluid change from water to typical oil (refractive index difference of 0.12), we report a wavelenght shift of up to 12 nm at the measurement wavelength of 1550 nm, in very good agreement with the simulations. We follow the optical response at a fixed wavelength, when feeding alternate flows or bubbles of oil/water through the optofluidic chip, and observe the flow pattern on camera. Finally we discuss the outlook and antifouling of

the sensor with a special design. This work is supported by Shell Global Solutions.

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10107-14, Session 4

Biophotonic applications integrated on chip through CMOS-compatible integrated SiN photonic waveguides

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Biophotonic based sensing or imaging relies often on expensive and bulky equipment. Integrated optics solutions could alleviate both cost and equipment size, by integrating the optical functionality on chip. It is beneficial to integrate this optical functionality directly on top of a CMOS chip, for detection and processing of the light and the information. We have developed a 200 mm CMOS compatible SiN waveguide platform with low losses at visible wavelengths. In this platform we have focused on a number of emerging applications, such as cytometry, localized fluorescent sensing and spectroscopy. We have demonstrated density controlled waveguide gratings for tailored out-coupling of light, and applied this to integrated excitation and detection of fluorescently tagged particles and cells. We have successfully demonstrated integrated excitation and collection of single cell passage using single mode waveguides and out-of-plane focusing grating couplers. In addition, we have shown integrated excitation and collection of molecular fluorescence using the evanescent field of single mode waveguides and demonstrated its surface sensitivity. We will also discuss novel architectures for on-chip spectrosocopy.

10107-15, Session 4

Monolithic integration of a plasmonic sensor with CMOS technology

Abdul Shakoor, Boon C. Cheah, Danni Hao, Mohammed Al-Rawhani, Bence Nagy, James P. Grant, Univ. of Glasgow (United Kingdom); Carl Dale, Neil Keegan, Calum J. McNeil, Newcastle Univ. (United Kingdom); David R. S. Cumming, Univ. of Glasgow (United Kingdom)

Integrating nanophotonic sensors with complementary metal oxide semiconductor (CMOS) technology promises to transform personalised medicine in the same way CMOS technology has revolutionised the computing and telecommunications industry. Despite the remarkable progress in the development of sensitive, high performance and miniaturized nanophotonic sensor chips, their use in everyday life is limited due to the requirement of external bulky and costly equipment required for their readout. In the present work we have removed this so called "chip in a lab" hurdle in the widespread applications of nanophotonic sensors by monolithically integrating an array of gold nanodiscs with a CMOS detector and demonstrated a compact plasmonic sensor system with direct electrical readout. As this is the first demonstration of monolithic integration of plasmonic sensors with CMOS detectors, we have introduced a new figure of merit, the change of voltage per refractive index unit (?V/RIU), for measuring the sensitivity of nanophotonic sensors. The electrical sensitivity of our plasmonic sensor system is measured to be 5.8 V/RIU. Integration of nanophotonic sensors with CMOS technology combines the advantages of both technologies leading to a high performance, portable and low cost sensor system with digital formats and having a broad range of applications especially in point-of-care diagnostics.

10107-16, Session 5

Monitoring and feedback control in silicon photonic circuits using intrinsic and extrinsic carrier generation *(Invited Paper)*

Andrew P. Knights, Dixon Paez, Zhao Wang, Liam Dow, McMaster Univ. (Canada)

The presentation will describe two optical monitoring schemes which do not rely of waveguide taps or heterogeneous integration. The first uses intrinsic carrier generation sites in the silicon waveguide (such as surface states); while the second relies on the introduction of lattice defects via inert ion implantation. For the former we will describe a feedback mechanism that stabilizes microring resonators, while for the latter we will demonstrate a power leveling system. It will be shown that intrinsic generation sites in microring resonators can generate 100's nAs for input coupling power of 100uW at 1550nm. The dependence of the magnitude of the photocurrent on the coupling condition of the ring will be described. Extrinsic photocarrier generation can be achieved with an efficiency dependent on the lattice defect concentration, the detector length and the post-implant annealing. We will discuss the advantages of these techniques over those requiring a physical waveguide tap.

10107-17, Session 5

Seminconductor photonic crystal membraionne lasers for 3D integration on chip *(Invited Paper)*

Weidong Zhou, Shih-Chia Liu, Deyin Zhao, Hongjun Yang, The Univ. of Texas at Arlington (United States); Mattias Hammar, KTH Royal Institute of Technology (Sweden); Zhenqiang Ma, Univ. of Wisconsin-Madison (United States)

Over the last few years, significant progresses have been made on photonic crystal based surface-emitting lasers on silicon. Both membrane-reflector VCSELs (MR-VCSELs) and bandedge effect based PCSELs have been reported with silicon based photonic crystal cavities and hybrid integrated compound semiconductor gain materials. In this talk, we will report recent advances in these laser structures. Lasing characteristics will be reported considering different coupling efficiencies for both low and room temperature operations. The lateral cavity size effect will also be discussed in making low threshold lasers with small cavity sizes. Finally the integration of other coupling structures will be discussed for beam routing in-plane.

10107-18, Session 5

integrated InAs/InP quantum-dot coherence comb lasers *(Invited Paper)*

Zhenguo Lu, Jiaren Liu, Philip J. Poole, Chun-Ying Song, John Webber, Linda Mao, Shoude Chang, Heping Ding, Pedro J. Barrios, Daniel Poitras, Siegfried Janz, National Research Council Canada (Canada)

Current communication networks needs to keep up with the exponential growth of today's internet traffic, and telecommunications industry is looking for radically new integrated photonics components for new generation optical networks. We at National Research Council (NRC) Canada have successfully developed nanostructure InAs/InP quantum dot (QD) coherence comb lasers (CCLs) around 1.55 ?m. Unlike uniform semiconductor layers in most telecommunication lasers, in these QD CCLs light is emitted and amplified by millions of semiconductor QDs less than 60 nm in diameter. Each QD acts like an isolated light source acting independently of its neighbours, and each QD emits light at its own unique

wavelength. The end result is a QD CCL is more stable and has ultra-low timing jitter. But most importantly, a single QD CCL can simultaneously produce 50 or more separate laser beams at distinct wavelengths over the telecommunications C-band. Utilizing those unique properties we have put considerable effort well to design, grow and fabricate InAs/InP QD gain materials. After our integrated packaging and using electrical feedback-loop control systems, we have successfully demonstrated ultra-low intensity and phase noise, frequency-stabilized integrated QD CCLs with the repetition rates from 10 GHz to 100 GHz and the total output power up to 60 mW at room temperature. We have investigated their relative intensity noises, phase noises, RF beating signals and other performance of both filtered individual channel and the whole CCLs. Those highly phase-coherence comb lasers are the promising candidates for flexible bandwidth terabit coherent optical networks and signal processing applications.

10107-19, Session 6

The mid-IR silicon photonics sensor platform *(Keynote Presentation)*

Lionel Kimerling, Juejun Hu, Anuradha M. Agarwal, Massachusetts Institute of Technology (United States)

Advances in integrated silicon photonics are enabling highly connected sensor networks that offer sensitivity, selectivity and pattern recognition. Cost, performance and the evolution path of the so-called 'Internet of Things' will gate the proliferation of these networks. The wavelength spectral range of 3-8um, commonly known as the mid-IR, is critical to specificity for sensors that identify materials by detection of local vibrational modes, reflectivity and thermal emission. For ubiquitous sensing applications in this regime, the sensors must move from premium to commodity level manufacturing volumes and cost. Scaling performance/cost is critically dependent on establishing a minimum set of platform attributes for point, wearable, and physical sensing. Optical sensors are ideal for non-invasive applications. Optical sensor device physics involves evanescent or intra-cavity structures for applied to concentration, interrogation and photo-catalysis functions. The ultimate utility of a platform is dependent on sample delivery/presentation modalities; system reset, recalibration and maintenance capabilities; and sensitivity and selectivity performance.

The attributes and performance of a unified Glass-on-Silicon platform has shown good prospects for heterogeneous integration on materials and devices using a low cost process flow. Integrated, single mode, silicon photonic platforms offer significant performance and cost advantages, but they require discovery and qualification of new materials and process integration schemes for the mid-IR. Waveguide integrated light sources based on rare earth dopants and Ge-pumped frequency combs have promise. Optical resonators and waveguide spirals can enhance sensitivity. PbTe materials are among the best choices for a standard, waveguide integrated photodetector. Chalcogenide glasses are capable of transmitting mid-IR signals with high transparency. Integrated sensor case studies of i) high sensitivity analyte detection in solution; ii) gas sensing in air and iii) on-chip spectrometry provide good insight into the tradeoffs being made en route to ubiquitous sensor deployment in an Internet of Things.

10107-20, Session 6

Hybrid integration of carbon nanotubes in silicon photonic structures *(Invited Paper)*

Elena Durán-Valdeiglesias, Weiwei Zhang, Carlos Alonso-Ramos, Xavier Le Roux, Samuel Serna, Thi-Hong-Cam Hoang, Delphine Marris-Morini, Eric Cassan, Ctr. de Nanosciences et de Nanotechnologies (France); Francesca Intonti, Francesco Sarti, Niccolò Caselli, Federico La China, Massimo Gurioli, Univ. degli Studi di Firenze (Italy); Matteo Balestrieri, Arianna Filoramo, Commissariat à l'Énergie Atomique (France); Laurent Vivien, Ctr. de Nanosciences et de Nanotechnologies (France)

Optical interconnects based on silicon photonic devices are expected to overcome the copper link bottlenecks. However, the integration of all photonic structures including sources, modulators and detectors on the silicon platform is complex and not cost-effective due to the various used materials (Ge, InP, Si...)

We propose here to use carbon nanotubes (CNTs) integrated into silicon photonic devices for the development of light emitters. We report here on the study of the light emission coupling from CNTs into silicon optical resonators.

10107-21, Session 6

Silicon optical modulators for digital and analog optical communications *(Invited Paper)*

Lin Yang, Jianfeng Ding, Lei Zhang, Sizu Shao, Institute of Semiconductors (China)

Silicon photonics is considered as a promising technology to overcome the difficulties of the existing digital and analog optical communication systems, such as low integration, high cost, and high power consumption. Silicon optical modulator, as a component to transfer data from electronic domain to optical one, has attracted extensive attentions in the past decade. In this paper, we review the statuses of the silicon optical modulators for digital and analog optical communications and introduce our efforts on these topics. We analyze the relationship between the performance and the structural parameters of the silicon optical modulator and present how to optimize its performance including electro-optical bandwidth, modulation efficiency, optical bandwidth and insertion loss. The fabricated silicon optical modulator has an electro-optical bandwidth of 30 GHz. Its extinction ratios are 14.0 dB, 11.2 dB and 9.0 dB at the speeds of 40 Gbps, 50 Gbps and 64 Gbps for OOK modulation. The high extinction ratio of the silicon optical modulator at the high speed makes it very appropriate for the application of optical coherent modulation, such as QPSK and 16-QAM. The fabricated silicon optical modulator also can be utilized for analog optical communication. With respect to a noise floor of -165 dBc, the dynamic ranges for the second-order harmonic and the third-order intermodulation distortion are 90.8 dB and 110.5 dB respectively. By adopting a differential driving structure, the dynamic range for the second-order harmonic can be further improved to 100.0 dB while the third-order intermodulation distortion remains the same level.

10107-22, Session 6

GaSb-based single-mode distributed feedback lasers for sensing *(Invited Paper)*

James A. Gupta, Andrew Bezinger, Jean Lapointe, Daniel Poitras, Geof C. Aers, National Research Council Canada (Canada)

GaSb-based tunable single-mode diode lasers can enable rapid, highly-selective and highly-sensitive absorption spectroscopy systems for gas sensing. In this work, single-mode distributed feedback (DFB) laser diodes were developed for the detection of various trace gases in the 2-3.3um range, including CO2, CO, HF, H2S, H2O and CH4. The lasers were fabricated using an index-coupled grating process without epitaxial regrowth, making the process significantly less expensive than conventional DFB fabrication.

The devices are based on InGaAsSb/AlGaAsSb separate confinement heterostructures grown on GaSb by molecular beam epitaxy. DFB lasers were produced using a two step etch process. Narrow ridge waveguides were first defined by optical lithography and etched into the semiconductor. Lateral gratings were then defined on both sides of the ridge using electron-beam lithography and etched to produce the index-grating.

Effective index modeling was used to optimize the ridge width, etch depths and the grating pitch to ensure single-lateral-mode operation and adequate coupling strength. The effective index method was further used to simulate the DFB laser emission spectrum, based on a transfer matrix model for light transmission through the periodic structure.

The fabricated lasers exhibit single-mode operation which is tunable through the absorption features of the various target gases by adjustment of the drive current. In addition to the established open-path sensing applications, these devices have great potential for optoelectronic integrated gas sensors, making use of integrated photodetectors and possibly on-chip Si photonics waveguide structures.

10107-40, Session 6

Quantum state generation via integrated frequency combs *(Invited Paper)*

Piotr Roztocki, Michael Kues, Christian Reimer, Institut National de la Recherche Scientifique (Canada); Benjamin Wetzel, Institut National de la Recherche Scientifique (Canada) and Univ.of Sussex (United Kingdom); Fabio Grazioso, Institut National de la Recherche Scientifique (Canada); Brent E. Little, Xi'an Institute of Optics and Precision Mechanics, CAS (China); Sai T. Chu, City Univ. of Hong Kong (Hong Kong, China); Tudor Wyatt Johnston, Institut National de la Recherche Scientifique (Canada); Yaron Bromberg, Yale Univ. (United States); Lucia Caspani, Institut National de la Recherche Scientifique (Canada) and Heriot-Watt Univ. (United Kingdom); David J. Moss, Swinburne Univ. of Technology (Australia); Roberto Morandotti, Institut National de la Recherche Scientifique (Canada) and Univ. of Electronic Science and Technology of China (China)

The on-chip generation of optical quantum states will enable accessible advances for quantum technologies. We demonstrate that integrated quantum frequency combs (based on high-Q microring resonators made from a CMOS-compatible, high refractive-index doped-glass platform) can enable the generation of pure heralded single photons, cross-polarized photon pairs, as well as bi- and multi-photon entangled qubit states over a broad frequency comb covering the S, C, L telecommunications band, with photon frequencies corresponding to standard telecommunication channels spaced by 200 GHz.

Exploiting a self-locked, intra-cavity excitation configuration, a highly-stable source of multiplexed heralded single photons is demonstrated, operating continuously for several weeks with less than 5% fluctuations. The photon bandwidth of 110 MHz is compatible with quantum memories, and high photon purity was confirmed through single-photon auto-correlation measurements. In turn, by simultaneously exciting two orthogonal polarization mode resonances, we demonstrate the first realization of type-II spontaneous FWM (in analogy to type-II spontaneous parametric down-conversion), allowing the direct generation of orthogonally-polarized photon pairs on a chip.

By using a double-pulse excitation, we demonstrate the generation of time-bin entangled photon pairs. We measure qubit entanglement with visibilities above 90%, enabling the implementation of quantum information processing protocols. Finally, the excitation field and the generated photons are intrinsically bandwidth-matched due to the resonant characteristics of the ring cavity, enabling the multiplication of Bell states and the generation of a four-photon time-bin entangled state. We confirm the generation of this four-photon entangled state through four-photon quantum interference.

10107-38, Session PWed

Analysis on frequency response of trans-impedance amplifier (TIA) for signal-to-noise ratio (SNR) enhancement in optical signal detection system using lock-in amplifier (LIA)

Ji-Hoon Kim, Su-Jin Jeon, Chung-Ang Univ. (Korea, Republic of); Myung-Gi Ji, Jun-Hee Park, Chung-Ang university (Korea, Republic of); Young-Wan Choi, Chung-Ang Univ. (Korea, Republic of)

Lock-in amplifier (LIA) has been widely used in optical signal detection systems because it can measure low signal under high noise level. Generally, LIA used in optical signal detection system is composed of transimpedance amplifier (TIA), phase sensitive detector (PSD) and low pass filter (LPF). To improve the dynamic reserve (DR) of LIA the signal to noise ratio (SNR) should be improved. According to the analysis of frequency response of TIA, the noise gain can be minimized by proper choices of input capacitor (Ci) and feed-back network in the TIA in a specific frequency range. In this work, we have studied how to the SNR of TIA can be improved by a proper choice of frequency range that the SNR is improved when signal is detected in this frequency range, instead of detecting DC component. We have analyzed the way to control this frequency range through the change of passive component in the TIA. The result shows that the variance of the passive component in the TIA can change the specific frequency range where the noise gain is minimized in the uniform transimpedance

10107-39, Session PWed

The study of LED light source illumination conditions for ideal algae cultivation

Chun-Chin Tsai, Far East Univ. (Taiwan); Chien-Fu Huang, I-Shou Univ. (Taiwan); Guan-Hao Chen, National Univ. of Kaohsiung (Taiwan); Cheng-Feng Yue, Far East Univ. (Taiwan)

Utilizing LED light source modules with 3 different RGB colors, the illumination effect of different wavelengths had been investigated on the growth curve of the same kind of micro algae. It was found that the best micro algae culturing status came out with long wavelength light such as red light (650~670 nm). Based on the same condition for a period of 3 weeks , the grown micro algae population density ratio represented by Optical Density (O.D.) ratio is 1?0.4?0.7 corresponding to growth with Red, Green, Blue light sources, respectively. Mixing 3 types and 2 types of LEDs with different parameters, the grown micro algae population densities were compared in terms of O.D. Interestingly enough, different light sources resulted in significant discoloration on micro algae growth, appearing yellow, brown, green, etc. Our experiments results showed such discoloration effect is reversible. Based on the same lighting condition, micro algae growth can be also affected by incubator size, nutrition supply, and temperature variation. In recent years, micro algae related technologies have been international wise a hot topic of energy and environmental protection for research and development institutes, and big energy companies among those developed countries. There will be an economically prosperous future. From this study of LED lighting to ideal algae cultivation, it was found that such built system would be capable of optimizing artificial cultivation system, leading to economic benefits for its continuous development.

10107-23, Session 7

Silicon plasmonic microring modulator using embedded conducting oxides

Aya O. Zaki, The American Univ. in Cairo (Egypt) and Ain Shams Univ. (Egypt); Khaled A. Kirah, Ain Shams Univ. (Egypt); Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

Silicon photonics offer a promising solution to high speed chip-to-chip interconnects implied by the next generation of computing and communication systems. Electro-optical modulators are the key devices enabling data to be imparted onto an optical carrier wave to propagate in silicon photonic links. Modulators that utilize transparent conducting oxides as the electro-optical active layer in hybrid plasmonic waveguides have recently received a lot of attention. However, no study has considered embedding the conducting oxide in hybrid plasmonic ring and disk structures. In this paper, we propose a novel hybrid plasmonic micro-ring modulator employing an indium-tin-oxide (ITO) layer on silicon-on-insulator (SOI) platform. A pure standard silicon access waveguide is introduced and a detailed discussion of the coupling junction design is presented. Due to its unique electro-optical properties, a unity order change in the refractive index of ITO is attainable and exploited to make a significant shift in the resonance wavelength eliminating the need for high quality factor resonance without sacrificing power consumption. Unlike conventional ring modulators, the proposed modulation mechanism uses the combined effect of changes in both the real and the imaginary parts of the refractive index to control the resonance wavelength and extinction ratio. We comprehensively study the design trade-offs and their influence on the modulator performance and the transmission spectrum using FDTD simulations. Optimization of the design leads to a high modulation depth of about 20 dB for an applied voltage < 2V. The design has a small footprint of 3.2 µm2 and estimated total capacitance around 9 fF.

10107-24, Session 7

Gbit/s-operation of graphene electro-absorption modulators in a passive polymer waveguide platform for data and telecommunications

Moritz Kleinert, Philipp Reinke, Heinz-Gunter Bach, Walter Brinker, Crispin Zawadzki, Andreas Dietrich, David de Felipe, Norbert Keil, Martin Schell, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

Graphene with its high carrier mobility as well as its tunable light absorption is an attractive active material for high-speed electro-absorption modulators (EAMs). Large-area CVD-grown graphene monolayers can be transferred onto arbitrary substrates to add active optoelectronic properties to intrinsically passive photonic integration platforms.

In this work, we present graphene-based EAMs integrated in passive polymer waveguides. To facilitate modulation frequencies in the GHz range, a 50 ? termination resistor as well as a DC blocking capacitor are integrated with graphene EAMs for the first time.

Static transmission measurements show almost wavelength-independent absorption with little voltage-dependent hysteresis. Large signal data transmission experiments were carried out across the O, C and L optical communications bands. The fastest devices exhibit a 3-dB bandwidth of more than 4 GHz. Our analytical model of the modulation response for the graphene-based EAMs is in good agreement with the measurement results. It predicts that bandwidths greater than 50 GHz are possible with future device iterations.

Owing to the absorption properties of the graphene layers, the devices are expected to be functional at smaller wavelengths of interest for optical interconnects and data-communications as well, offering a novel flexibility for the integration of high-speed functionalities in optoelectronic integrated circuits. Our work is the first step towards an Active Optical Printed Circuit Board, hiding the optics completely inside the board and thus removing entry barriers in manufacturing. We believe this will lead to the same success as observed in Active Optical Cables for short range optically wired connections.

10107-25, Session 7

Metal-capped silicon organic micro-ring electro-optical modulator

Aya O. Zaki, The American Univ. in Cairo (Egypt) and Ain Shams Univ. (Egypt); Khaled A. Kirah, Ain Shams Univ. (Egypt); Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

An ultra-compact hybrid plasmonic waveguide ring electro-optical modulator is designed to be easily fabricated on silicon on insulator (SOI) substrates using standard silicon photonics technology. The proposed waveguide is based on a buried standard silicon waveguide of height 220 nm topped with polymer and metal. The key advantage of this novel design is that only the silicon layer of the waveguide is structured as a coupled ring resonator. Then, the device is covered with electro-optical polymer and metal in post processes with no need for lithography or accurate mask alignment techniques. The simple fabrication method imposes many design challenges to obtain a resonator of reasonable loaded quality factor and high extinction ratio. Here, the performance of the resonator is optimized in the telecom wavelength range around 1550 nm using 3D FDTD simulations. The design of the coupling junction between the access waveguide and the tightly bent ring is thoroughly studied. The extension of the metal over the coupling region is exploited to make the critical dimension of the design geometry at least 2.5 times larger than conventional plasmonic resonators and the design is thus more robust. In this paper, we demonstrate an electro-optical modulator that offers an insertion loss < 1 dB, a modulation depth of ~12 dB for an applied peak to peak voltage of only 2 V and energy consumption of ~1.74 fJ/bit. The performance is superior to previously reported hybrid plasmonic ring resonator based modulators while the design shows robustness and low fabrication cost.

10107-26, Session 7

Tapered graded-index core polymer waveguide for very short light path fabricated using the imprint method

Kenji Katori, Takaaki Ishigure, Keio Univ. (Japan)

In this paper, we propose a tapered graded-index (GI) core polymer optical waveguide with only 300-micrometer length for applying to a very short light path such as optical VIA and optical pin. The tapered GI core polymer waveguides are actually fabricated utilizing the imprint method. We theoretically and experimentally demonstrate that tapered GI core polymer waveguides exhibit lower loss (1 dB or more) than tapered step-index (SI) core waveguides.

In recent years, the data traffic in datacenters has grown rapidly due to the deployment of cloud services. In order to support this growth, optical interconnection technologies are gradually deployed and approaching to short-reach regions in the vicinity of LSI chips. Hence, a low loss very short optical path that perpendicularly passes through printed circuit boards (PCBs) or interposers are required. The optical VIA in PCBs and optical pin in optical transceivers are the examples. In such a short optical path, a tapered waveguide structure has been reported. However, the excess loss due to the scattering at the core-cladding interface and the increase in the divergence angle of the output light would be problems in the current SI core waveguide based optical VIA and optical pin.

Therefore, we focus on GI core waveguides in this paper, because GI core

waveguides confine the propagating modes strongly to the center of the core. In addition, the short GI-cores play a role of GRIN (convex) lenses, as well. So, the output NA from tapered GI core waveguides is optimized by adjusting the waveguide parameters.

10107-27, Session 7

Study of an array of grating couplers for wireless optical communications

Shahryar Sabouri, Meysam Namdari, Seyedreza Hosseini, Kambiz Jamshidi, TU Dresden (Germany)

Grating couplers have been widely studied to be used as an interface for photonic integrated circuits. These structures are able to convert waveguide mode to radiation mode, or vice versa and can largely be employed for point-to-point communications system. In order to realize an array of such systems, a linear grating coupler is designed in SOI platform to provide maximum directional radiation [1]. A rib waveguide with a silicon thickness of 220nm and an etch depth of 70nm using 2?m silica substrate is designed in order to feed radiative elements. TE polarized input light with wavelength of 1550nm is coupled into the waveguide. Radiated main beam of grating coupler is optimized based on its angular coverage, directed power, and beam efficiency.

In order to obtain more concentrated power and higher gain, phased array structure can be used. Moreover, illuminating small footprints in a far distance from transmitter requires narrow beam width, which cannot be easily achieved by a single antenna. Therefore, a phased array consisting of optimized grating structures is investigated. The distance between consequent elements is optimized to amplify main lobe of radiation for array structure and the coupling efficiency between transmitter and receiver is studied accordingly [2]. Finally, beam steering abilities in both polar and azimuthal angles using an array of couplers are investigated [3]. Performance trade-offs in terms of coverage, tunability, and efficiency are discussed accordingly.

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10107-28, Session 8

Graphene planar lightwave circuit sensors for chemical detection

Ashok Maliakal, Saima Husaini, Leslie A. Reith, Paul Bollond, Steve Cabot, LGS Innovations Inc. (United States)

Sensing devices based on Graphene Field Effect Transistors (G-FET) have been demonstrated by several groups to show excellent sensitivity for a variety of chemical agents. These devices utilize changes in the electrical conductivity of graphene upon chemical exposure. In addition, graphene also exhibits changes in its optical response upon chemical exposure as a result of its unique band structure. The conical intersection of the valence and conduction bands results in a low density of states near the Dirac point. At this point, chemical doping resulting from molecular binding to graphene can result in dramatic changes in graphene's optical absorption. Here we will discuss our recent work in developing a graphene planar lightwave circuit (PLC) sensor which exploits these optical and electronic properties of graphene for chemical detection. The devices are based on a strong evanescent coupling of graphene via electrically gated silicon nanowire waveguides. A strong response in the form of a reversible optical attenuation change of 6 dB is shown when these devices interact with toxic industrial chemicals such as iodine and ammonia. The optical transition can also be tuned to the optical c-band (1530-1565 nm) which allows these devices to operate at telecom wavelengths.

10107-29, Session 8

Silicon photonics waveguide array chemical sensor with integrated read-out

Ricardo Janeiro, Raquel Flores, Jaime Viegas, Masdar Institute of Science & Technology (United Arab Emirates)

Chemical sensing is usually achieved in photonics platforms by monitoring spectral changes on the output of a passive photonic element due to the modulation of the refractive index of core and cladding. Therefore, compact interferometers are usually sought for the embodiment of refractometer sensors. We present our work on refractive index sensors based on arrayed waveguide interference, which are built on a Silicon-On-Insulator (SOI) platform. A comparative study of two configurations, resonant and non-resonant is presented. In both cases the main design is based on a set of closely placed single mode waveguides. The distance between waveguides is such that directional coupling occurs. Moreover, when the distance between the waveguides is small comparatively to the transversal exponential decay length of the eigenmode of the waveguide, there is an enhancement effect of the electric field in the region between the waveguides, as usually seen for slotted waveguides. The reported sensors include multiple parallel slotted waveguides which are the core of the sensor. Non-resonant configuration incorporates straight waveguides from which the output can be directly imaged onto a CCD array for direct sensor read-out, while the resonant layout presents a set of concentric racetrack waveguides designed for light extended lifetime, enhancing the sensor sensitivity. A top polymer cladding is used to encapsulate the waveguides providing a permeable low index material. This cladding material acts as the transducer element, changing its optical properties when in contact with a chemical of interest, therefore allowing for high sensitivity and chemical selectivity.

10107-30, Session 8

Use of photonic jets produced by dielectric microspheres for increasing sensitivity and angle-of-view of MWIR detectors

Farzaneh Abolmaali, The Univ. of North Carolina at Charlotte (United States); Aaron Brettin, University of north Carolina at Charlotte (UNCC) (United States); Nicholaos I. Limberopoulos, Augustine M. Urbas, Air Force Research Lab. (United States); Vasily N. Astratov, The Univ. of North Carolina at Charlotte (United States) and Air Force Research Lab. (United States)

The designs of modern focal plane arrays (FPA) used in mid-wave infrared (MWIR, ?~3-5 μm) detectors develop towards minimization of the pixel sizes and increasing the operational temperature. The operating temperature can be increased by minimizing the active volume of the detector due to reduction of the dark current. All these designs require highly efficient collection of light into such small mesas which in principle can be achieved by using photon trap structures such as photonic crystals or textured surfaces with pyramidal relief features. However, the angular operation range of such structures can be rather limited. To simultaneously increase the light collection efficiency, angle-of-view (AOV) and operating temperature of MWIR FPAs, in our recent work we suggested using "photonic jets", sharply focused beams with subwavelength transversal width produced by dielectric microspheres. In our designs, spheres are integrated with individual pixels. In this work, using numerical modeling, we optimized our designs for achieving maximal AOVs for spheres with

different diameters in 30-60 ?m range, as well as with various indices of refraction and modified shapes including truncated spheres. We show that microspheres allow AOVs an order of magnitude higher compared to standard microlens arrays. We demonstrate AOVs up to 20 deg for front- and 8 deg for back-illuminated structures combined with high light collection efficiency.

10107-31, Session 9

Indoor visible light communication with smart lighting technology *(Invited Paper)*

Abhirup Das Barman, Univ. of Calcutta (India); Alak Halder, Univ. of Calcutta (India) and Institute of Radio Physics and Electronics (India)

An indoor short range visible-light communication performance improvement is investigated utilizing energy efficient white light by 2D LED arrays in the wavelength range from 380 nm to 780 nm. Nitride based highly efficient blue and green LEDs have become commercially available. By mixing three primary colors (red, green and blue) white light can be produced. Enabled by recent advances in LED technology, IEEE 802.15.7 standardizes high-data-rate visible light communication up to 96 Mb/s by fast modulation of optical light sources. The standard is capable of delivering data rates sufficient to support audio and video multimedia services. The IEEE 802.15.7 physical (PHY) types III speaks for colour shift keying (CSK) modulation which overcomes two main challenges faced by the conventional intensity modulation and pulse position modulation in terms of flicker reduction and dimming support. Designing higher order multilevel (N) CSK constellation for high bit rate system following the standard CIE (1931) colour chromaticity coordinates and its decoding strategy at the receiver is a challenging task. Voronoi segmentation is employed for decoding N-CSK constellation which provides superior performance compared to other existing decoding methods in terms of better received signal to noise ratio and symbol error rate. LED nonlinearity is particularly severe for higher order N-CSK where distance between signal constellations is reduced. The two chief performance degrading effects of inter-symbol interference and LED nonlinearity is jointly mitigated using LMS post equalization technique at the receiver. The strategy improves symbol error rate performance with increased field of view in the reception.

10107-32, Session 9

Enhanced electroluminescent cooling in GaN-based light-emitting diodes *(Invited Paper)*

Joachim Piprek, NUSOD Institute LLC (United States); Simon Z. M. Li, Crosslight Software Inc. (Canada)

Optimized GaN-based light-emitting diodes (LEDs) were recently demonstrated to emit photons of higher energy than the injected electrons up to elevated currents beyond the peak of the power conversion efficiency. Correspondingly, the electrical efficiency is above unity, which is attributed to heat extraction from the crystal lattice. In good agreement with measurements, we investigate the origin of such electroluminescent cooling by advanced numerical simulation including all relevant heat transfer mechanisms. For the first time, our simulations reveal the magnitude and the local profile of the heat extraction from the lattice. The built-in nitride polarization field is found to enhance the cooling effect significantly.

10107-33, Session 9

The integration of InGaP LEDs with CMOS on 200-mm Silicon wafers

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The integration of photonics and electronics on a converged Si CMOS platform is a long pursuit goal for both academic and industry. In SMART we have been developing the technologies that can integrate III-V compound semiconductors and Si CMOS on 200 mm Si substrates. As an example we will present our work on the integration of InGaP red LEDs with CMOS on 200 mm Si wafers. The InGaP LEDs are epitaxially grown on 200 mm Si wafers using high-quality Ge and GaAs buffers in MOCVD reactor. Due to the mismatch of coefficients of thermal expansion (CTEs) between III-V and Si, the LED wafers were bowed significantly after epitaxy. Strain engineering was applied to control the wafer bow to be low enough for subsequent processing. Wafer bonding was used to transfer the Si CMOS layer to the LED wafers. After removed the Si handle wafer, trenches were opened on the CMOS layer to expose the underneath III-V for LED processing. The interconnects between LEDs and CMOS circuits will be done after LED finished. We will address the issues encountered in the 200 mm processing, including the etching, the CMOS-compatible metal contact development for III-V, and the methods we have been developing to overcome the problems.

10107-34, Session 9

Integrated long-cavity mode-locked ring laser with output boost amplifier

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We aim to develop photonic integrated circuits (PICs) for the generation and distribution of frequency standards and calibration signals of very high quality by photonic techniques. There are different techniques for generating radiofrequencies. Photonic techniques have a number of advantages over electronic, among which is the possibility of using fiber optics to transport signal with very low propagation loss. Furthermore, photonic techniques have additional advantages such as the quality of the signal generated (low phase noise), the tuning range of the generated frequency and bandwidth modulation. Photonic signal generation techniques are based on optical heterodyning (Dual Wavelength Laser Source), or pulsed lasers (Mode-Locked Laser Source). Each of the techniques has its own quality features and tuning range. The main advantage of the solution provided by the pulsed lasers is that they offer stable signal generation, directly producing a frequency comb. We report an integrated 30 mm long cavity mode locked ring laser at 1555 nm, with a low repetition rate at 2.7 GHz which acts an Optical Frequency Comb Generator (OFCG). The device uses InP-based active-passive integration technology and an output boost amplifier. Passive (PML) and hybrid mode locked (HML) operation are experimentally demonstrated, with picosecond pulses of 4.65 ps and 4.23 ps pulse-widths respectively. The device exhibits a very narrow RF linewidth of the beat note of few KHz. Also we evaluate the phase noise performance of the fundamental signal generated in both regimes PML and HML.

10107-35, Session 10

Design and implementation of 3D LIDAR based on pixel-by-pixel scanning and DS-OCDMA

Gunzung Kim, Jeongsook Eom, Yongwan Park, Yeungnam Univ. (Korea, Republic of)

In the previous paper, we proposed a new 3D LIDAR system, which measures a scene with 1280x600 pixels at a frame rate of 60fps. The emitted pulses of each pixel are coded by direct sequence optical code division multiple access techniques. The LIDAR emits the coded pulses periodically without idle listening time to receive returning light at the detector. When all the pixels are completely through the process, the travel time, amplitude, width, and speed are used by the pixel-by-pixel scanning LIDAR to generate point cloud data as the measured results.

In this study, we present implementation of the proposed 3D LIDAR system. We picked up the OPM-LDa-gs as an optical laser pulser that has an adjustable pulse generator from gain-switched operation from 60ps to 1ns. To convert received laser pulses into electrical pulses, we used the EOT's ET-4000AF that is a 9GHz amplified high-speed fiber photodetector with PIN photodiode. We selected the MirrorcleTech MEMS mirror development kit as a two-axis MEMS mirror. This deflects laser pulses anywhere in a 30-degree field of regard cone. We chose the TI's 66AK2L06 evaluation module for signal processing and the ADC12J4000 evaluation module for analog-to-digital conversion. The 66AK2L06 evaluation module is equipped two 1.2GHz ARM Cortex-A15 cores, and four 1.2GHz TMS320C66x DSP cores with an integrated digital front end and a JES204B interface, enabling seamless connection to 4GHz ADC12J4000 evaluation module. With these modules, we implemented a simplified model of the proposed 3D LIDAR system, and we will show the operations and results.

10107-36, Session 10

2D intensity images from sparse LIDAR data in urban environment

Imran Ashraf, Yongwan Park, Yeungnam Univ. (Korea, Republic of)

Light Detection And Ranging (LIDAR) has become part and parcel of ongoing research in remote sensing. Although LIDAR efficiently captures data during day and night alike, yet data accuracy is affected involving altered weather conditions. LIDAR data fusion with sensors like color camera, hyperspectral camera and RADAR proves to be a viable solution not only to improve quality of data but to produce high definition color data; as LIDAR cannot capture color information and is low resolution. LIDAR 3D point cloud is transformed in 2D intensity images for the said purpose. In spite that LIDAR produces a large number of points per frame (between 1 to 1.3 million for 360° scan), while generating images for limited Field of View (FoV) data sparsity results in poor quality images. Moreover, 3D to 2D data transformation also involves data loss which further deteriorates the quality of images. This research focuses on generating intensity images from LIDAR data by utilizing interpolation techniques including Bi-linear, Nearest Neighbor and Bi-cubic interpolation. The main focus is to test the suitability of interpolation methods for 2D image generation, evaluate the performance of interpolation methods and analyze the quality of the generated 2D image. Furthermore, since the generated images contain noise and blur; Symmetric Median, Weiner, Hybrid Median filter and morphological operations are used to improve the quality of images. Generated images can further be used for data fusion purpose. Results show that Bi-linear interpolation and Symmetric Median filter outperforms other selected methods.

10107-37, Session 10

Effects of rain, fog, and snow on LIDAR data in urban environment

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Light Detection And Ranging (LIDAR) offers univocal means of data capturing in remote sensing. It can collect intensity and distance data during day and night alike, albeit with limitations in accuracy due to weather conditions. Owing to weather conditions factors affecting the performance of LIDAR intensity data include rain, haze, fog and snow. The effect of weather is twofold: scattering by aerosol and absorption by the presence of water drops. The prime objective of this research is to investigate how these weather conditions strike the quality of LIDAR intensity data. Experiment is carried out for rain, fog and snow using Velodyne HDL-64E with 905nm wavelength. For experiment rain is classified into three categories (light, moderate and heavy) based on the magnitude of water drops. For fog a similar approach is adopted for the cases of light and heavy fog. Since snow contains snowflakes of different sizes so, radius of snowflake is considered to classify it into light, moderate and heavy snow. Dry and wet snow are regarded as appropriate classes of snow considering the presence of water, henceforth both are studied separately. Because theoretical approaches based on microphysical models are very complex and time consuming; hence, atmospheric attenuation of laser beam is calculated using empirical model which is based on visibility range estimate. Results show that LIDAR data has less contrast for fog and snow while severe deterioration in intensity data is found due to absorption in rain. Experiment also show that LIDAR sensing rage is reduced due to attenuation.

10108-1, Session 1

Passively Biased Resonantly Enhanced Silicon Photonics Modulator with High Optical Bandwidth *(Invited Paper)*

Jeremy Witzens, Sebastian Romero-García, Alvaro Moscoso-Mártir, Bin Shen, Saeed Sharif Azadeh, Jovana Nojic, Florian Merget, RWTH Aachen Univ. (Germany)

Mainstream configurations of Silicon Photonics modulators are two-fold: ring resonator modulators (RRM) and Mach-Zehnder modulators (MZM). RRMs leverage the resonance enhancement to reach high modulation efficiencies, are very compact and can be electrically driven as lumped elements. However, the resonant enhancement also limits their optical bandwidth so that temperature stabilization is required, limiting their power efficiency. On the other hand, MZMs need long phase shifters or high drive voltages to reach high extinction. Furthermore, although a symmetric configuration enables very large optical bandwidths, the compensation of fabrication asymmetries accumulating over long MZM arms requires a corrective phase tuner.

A novel MZM modulator addresses these issues and aggressively reduces power consumption. An integration scheme passively sets the 3 dB point during attachment of the input fiber relative to a misalignment tolerant multimode grating coupler also used as the first splitter element of the interferometer. Second, straight phase shifters are replaced by arrays of highly overcoupled resonators. The challenge lies in maintaining a sufficiently high finesse and a substantial resonant enhancement while minimizing the excess losses at the resonator to waveguide junctions. With a novel resonator design, we achieve a very compact cavity size and thus an acceptable finesse notwithstanding the low quality factor of the resonant phase shifter elements. A large resonance bandwidth compatible with a wide thermal operation range of more than 25oC without dynamic compensation is obtained together with a reduction of power consumption by a factor seven relative to a conventional MZM relying on the same pn junction configuration.

10108-2, Session 1

New materials for modulators and switches in silicon photonics *(Invited Paper)*

Dries Van Thourhout, Univ. Gent (Belgium); Marianna Pantouvaki, IMEC (Belgium); Herbert D'Heer, Koen Alexander, Bart Kuyken, Univ. Gent (Belgium); Inge Asselberghs, Steven Brems, Cedric Huyghebaert, IMEC (Belgium); Leili Abdollahi Shiramin, Univ. Gent (Belgium); Chiara Alessandri, IMEC (Belgium); John P. George, Jeroen Beeckman, Univ. Gent (Belgium); Min-Hsiang Hsu, Clement Merckling, Joris Van Campenhout, IMEC (Belgium)

In this presentation we will report on our recent work on new materials that can be monolithically integrated on high-index contrast silicon or silicon nitride photonic ICs to enhance their functionality. This includes graphene and other 2D-materials for realizing compact electro-absorption modulators and non-linear devices, ferroelectric materials for realizing phase modulators and adiabatic couplers for realizing bistable switches.

10108-3, Session 1

Numercial analysis and optimization of high-speed microring resonator modulators using high-performance carrier-depletion phase shifters

Thomas Y. L. Ang, Jason Png, Soon Thor Lim, A*STAR Institute of High Performance Computing (Singapore)

Silicon microring resonator modulators are versatile active on-chip devices capable of high-speed modulation with low energy consumption. However, the effects of PN junction alignment variance for different doping concentrations during fabrication have not been thoroughly looked into. In this work, we numerically demonstrate and analyze the optimization of the silicon microring resonator modulator based on the carrier depletion mechanism for high extinction ratio and low energy consumption at the communication wavelength of 1550 nm. A range of carrier doping concentrations and offset of the PN junction to the waveguide centre can be used to optimize the modulation efficiency, energy consumption and insertion losses of the microring modulator. In particular, the effects of the offset of the PN junction in microring resonators of different size and waveguide-to-ring evanescent coupling strengths are analyzed for three different cases: (i) p-type doping < n-type doping, (ii) p-type doping = n-type doping, and (iii) p-type doping > n-type doping. Three common types of microring ring modulator architecture – the all-pass microring resonator, the add-drop microring resonator, and the all-pass dual coupled microring resonator – are analyzed, and numerically optimized. Our results suggest that doping concentration between 2 x 10e17 cm-3 to 5 x 10e17 cm-3, with the p-doping concentration lower than the n-doping concentration, should be employed in order to achieve a tunability of > 0.016 nm/V and extinction ratio of > 8 dB.

10108-4, Session 1

All-Optical Switch with 1 ps Response Time Enabled by Graphene Oxide Infiltrated Subwavelength Grating Waveguide

Xiaochuan Xu, Omega Optics, Inc. (United States); Zeyu Pan, The Univ. of Texas at Austin (United States); Baohua Jia, Swinburne Univ. of Technology (Australia); Yaguo Wang, Ray T. Chen, The Univ. of Texas at Austin (United States)

Driven by bandwidth hungry technologies such as online video and cloud computing, the skyrocketing growth of global data traffic has no sign of halting. As the desire for large bandwidth permeates optical interconnects such as core networks and data centers, electronic switches must be abandoned when speed is beyond 100 Gbps. To accommodate the bandwidth demand, all-optical switches must be adopted in the near future. Silicon photonics is the most promising platform for all-optical switching. The high refractive index of silicon can minimize footprint and maximize bandwidth density, and the mature silicon electronics fabrication technology can be leveraged to massively produce photonic devices at a low cost. However, two-photon absorption and free carrier absorption induced loss degrades the switches' performance. Hybrid integration of third-order nonlinear materials is a promising alternative, but its performance is limited by the small mode volume overlap between the third-order nonlinear material and the optical mode. In this paper, we propose and demonstrate an all-optical switch using graphene oxide infiltrated subwavelength grating waveguide. Benefiting from the extremely large Kerr coefficient of graphene oxide (four orders of magnitude larger than conventional materials) and large mode volume overlap factor of the subwavelength grating waveguide (4~10 times larger than conventional strip waveguides), the switch is capable of achieving THz speed with less than 1 fJ energy consumption per

bit, which is more than three orders of magnitude smaller than THz switches reported so far.

10108-5, Session 1

High speed and low power consumption modulator based on electro-optic polymer infiltrated subwavelength grating waveguide ring resonator

Zeyu Pan, The Univ. of Texas at Austin (United States); Xiaochuan Xu, Omega Optics, Inc. (United States); Yaguo Wang, The Univ. of Texas at Austin (United States); Baohua Jia, Swinburne Univ. of Technology (Australia); Ray T. Chen, The Univ. of Texas at Austin (United States)

Silicon-based high-speed optical modulators, fabricated using CMOS compatible nanofabrication technology, are the key components for integrated photonics, especially the high-speed intra- and inter-chip optical interconnects. In this paper, we propose a high speed, low power consumption electro-optic (EO) modulator based on the EO polymer/silicon hybrid subwavelength grating (SWG) waveguide ring resonator. The core of the SWG waveguide consists periodically arranged silicon pillars along the light propagation direction. EO polymer (SEO125) is used as the top cladding. An intriguing advantage that the SWG waveguide has over the conventional silicon strip waveguide is its large mode volume overlap with EO polymer. Besides, compared with the plasma dispersion effect, electro-optic polymers have a large electro-optic coefficient and ultrafast response speed. Furthermore, among the different modulator structures, ring resonator is one of the most promising structures as it has a small footprint which is the key for VLSI (Very Large Scale Integration), and it allows complex optical functionalities monolithically integrated with advanced electronics at a competitive cost. Thus, the proposed EO polymer infiltrated SWG waveguide ring resonator based modulator is a very promising candidate for low cost, small size, light weight, and low power consumption (CSWaP) optical interconnect.

10108-6, Session 2

The impacts of fabrication error on spectral variation of silicon grating couplers

Tsuyoshi Horikawa, National Institute of Advanced Industrial Science and Technology (Japan) and Photonics Electronics Technology Research Association (Japan); Jun Ushida, Yohei Sobu, Photonics Electronics Technology Research Association (Japan); Daisuke Shimura, Photonics Electronics Technology Research Association (Japan); Akemi Shiina, Masatoshi Tokushima, Seok-Hwan Jeong, Keizo Kinoshita, Tohru Mogami, Photonics Electronics Technology Research Association (Japan)

In optical ICs using silicon photonics technology, silicon grating couplers (GCs) which consist of periodic trench structure are most important IO devices for optical coupling with fibers. The grating pitch and depth of GC are designed to maximize coupling efficiency between GCs and fibers for a wavelength of incident light. Cross-sectional size deviations in device fabrication cause spectral variation in the optical coupling.

In this study, we theoretically and experimentally investigated how fabrication errors impact on GC transmission spectrum. The GCs designed for a wavelength of 1300 nm were fabricated on 300-mm-diameter 200-nm-thick SOI substrates by using 40-nm-node CMOS technology with ArF immersion lithography, and were characterized by an automated optical wafer-level probing system. In the transmission spectra via GC-fiber coupling, it was confirmed that the coupling efficiency, peak wavelength, and transmission bandwidth (1dB) for 64 GCs on a 300-mm wafer are 2.99+/-0.07 dB, 1302.3+/-1.9 nm, and 31.1+/-0.8 nm, respectively. All of the deviation values (1sigma) for these properties are quite small, compared with previous studies by using dry excimer lithography technology. We also theoretically derive relationship between grating depth shift and peak wavelength shift, and confirm the validity of the theoretical relationship in fabricated GC's properties.

As the results of the study, we showed that fabrication error in grating formation is the main cause of spectral variation of GCs, and the usage of high-resolution process technology is a practical solution to improve spectral reproducibility in order to realize low-loss optical ICs.

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10108-7, Session 2

Silicon photonic device applications using micro-opto-electro-mechanical index perturbation

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Silicon photonics enables the development of optical components on a chip-scale platform with the potential for large-scale optical integrated circuits that can be fabricated at the wafer-scale using foundries similar to those used in the electronics industry. Although silicon is a passive optical material with an indirect bandgap, reconfigurable devices have been demonstrated using thermo-optic effects (large phase shifts, but slow with large power consumption) and carrier plasma dispersion effects (high-speed, but small phase shifts). We recently demonstrated [1] a low-power approach for inducing large phase shifts (>2pi) by way of micro-opto-electro-mechanical index perturbation (MOEM-IP). In this initial work we characterized silicon nitride waveguides in which the propagating optical mode's evanescent field is vertically coupled to silicon nitride microbridges. This interaction leads to an effective index tuning that is a strong function of the waveguide-microbridge separation. In this work we extend our MOEM-IP approach to different configurations (i.e. in-plane coupling) and material systems (i.e. silicon-on-insulator). Mode perturbation simulations indicate that the MOEM-IP approach is widely applicable to many configurations and material systems enabling large effective index tuning (>0.1) requiring microbridge displacements of only a few hundred nanometers. We also examine various device applications that take advantage of MOEM-IP. These include optical phased arrays [2] that enable chip-scale beam steering in two-dimensions using low-power phase shifting enabled by MOEM-IP. Other potential applications include widely tunable optical filters using high-Q microring cavities and sensitive transducers for RF-detection.

[1] Pruessner et al., Optics Express (2016)

[2] Mahon et al., SPIE Photonics West (2016)

10108-8, Session 2

Photonic crystal nanocavities with Q factor of 2 million fabricated by CMOS compatible process

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Photonic crystal nanocavities on silicon-on-insulator (SOI) wafers are attracting much attention because of their high quality factors (Q) and small modal volumes. There are many kinds of applications of nanocavities such as optical integrated circuits, biosensors, low-threshold lasers, and quantum information processing devices. Because these applications require wide ranges of Q factors from thousands to several millions, the nanocavities have been expanding the research fields with the increase of the Q values.

The nanocavities consist of periodic air holes with the radii of 100 nm. Previous calculation revealed that the variations of air holes with a standard deviation of as little as 1 nm decrease the Q values to approximately one million. Therefore, we have thus far devoted much effort to improve the fabrication process and recorded the Q of 10 million. However, such high-Q nanocavities were realized by using electron-beam lithography process which is time-consuming. Considering the future industry applications, it is important to fabricate the high-Q nanocavities using CMOS compatible process. In this study, we report the high-Q nanocavities fabricated on 300 mm SOI wafer using 193 nm ArF immersion lithography. We fabricated the multi-step heterostructure nanocavities and the 8-channel drop filters consisting of shift-L3 arrayed nanocavities. In multi-step heterostructure nanocavities, the highest Q-factor of 2 million and the average value of 1.5 million were obtained. These values are the highest reported so far for the nanocavities using CMOS compatible process. In addition, the 8-channel drop filters indicated the good properties with the 200 GHz spacing.

10108-9, Session 2

Broad-band silicon bridge waveguide polarization beam splitter

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We have successfully fabricated and measured the polarization beam splitter (PBS) based on bridge waveguide, sandwiched between a direction coupler using a multi-project wafer (MPW) shuttle runs. Our experimental results demonstrated high extinction ratio of > ~15 dB over the entire C band for both TE-like and TM-like polarizations with a small footprint of ~18?9 ?m2. Our results demonstrated that our PBS allows the input light to be separated into the TM-like mode at the cross port (T = ~0 dB), and the TE-like mode at the through port (T = ~ 0 dB). Due to the use of the bridge waveguide, residual TE-like light at the cross port has been significantly suppressed to ~ -23 dB across the bandwidth of 100 nm. Likewise, residual TM-like light at the through port is also considerably suppressed to < -20 dB across the bandwidth of 100 nm, with an ER as high as ~35 dB at ? = 1570 nm. The importance of a PBS is the need for polarization diversity in an integrated photonics, for example, in a dual-polarization quadrature phase-shift keying (DP-QPSK) modulation setups. However, due to the stringent condition of a standard foundry processes, the optical performance of the PBS might be significantly affected, which in term increase the cost and accessibility. To provide our PBS suitable for large scale silicon photonics manufacturing, we also studied PBS for design of experiment, taking into account processes restriction and constraint.

10108-10, Session 2

Second order add/drop filter with a single ring resonator

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We show theoretically and experimentally how a flat-top second-order response can be achieved with a self-coupled single add-drop ring resonator based on two couplers with different splitting ratios. The resulting device is a 1x1 filter, reflecting light back in the input waveguide at resonating wavelengths in the passbands, and transmitting light in the output waveguide at all other non-resonating wavelengths. Different implementations of the filter have been designed and fabricated on a micron-scale silicon photonics platform. They are based on compact Euler bends - either U-bends or L-bends - and Multi-Mode Interferometers as splitters for the ring resonators. Different finesse values have been achieved by using either 50:50 MMIs in conjunction with 85:15 MMIs or 85:15 MMIs in conjunction with 95:05 double MMIs. Unlike ordinary lowest order directional couplers, the MMIs couple most of the power in the cross-port which make them particularly suitable for the topology of the self-coupled ring, which would otherwise require a waveguide crossing. Experimental results are presented, showing good agreement with simulations. The proposed devices can find applications as wavelength-selective reflectors for relatively broad-band lasers or used as 2x2 add-drop filters when two exact replicas of the device are placed on the arms of a Mach-Zehnder interferometer.

10108-12, Session 3

Inductively Coupled Plasma etching of Germanium Tin for the fabrication of photonic components

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Since the beginning of silicon photonics, demonstration of a CMOS compatible laser working at room temperature has always been eagerly sought after. Although bulk Germanium (Ge) is an indirect bandgap material, one can incorporate some Tin (Sn) to turn it into a direct semiconductor. A lasing effect has recently been demonstrated at cryogenic temperatures using a quasi-relaxed Ge0.98Sn0.12 alloy [1]. To increase the working temperature, one challenging way is to incorporate very high Sn concentrations in the Ge crystalline matrix. However, for high Sn content it induces a compressive stress which is difficult to handle and harmful for the optical properties as it increases the direct bandgap faster than the indirect bandgap.

It is thus necessary to control and measure accurately the stress in GeSn devices. Here we report our latest results on bandgap and strain in GeSn layers and heterostructures using photoluminescence, XRD and Raman spectroscopy. We first detail strain and Sn content measurements on high Tin concentration Ge(1-x)Snx layers up to 15%. Then we present micro-structures designed to finely relax the stress and study its influence. Finally, PL spectroscopy is performed to measure the bandgap-strain relationship over a large range of Sn contents. To conclude, we compare our experimental data to a model based on deformation potentials. These results will give a better understanding of Ge/GeSn heterostructures as gain media for mid-infrared lasers compatible with CMOS technology.

[1] Wirth, S. et al. Nature Photonics 9, 88–92 (2015)

10108-13, Session 3

Luminescence of strained Ge on GeSn virtual substrate grown on Si (001)

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To enlarge the tensile strain in Ge light emission diodes (s-Ge LED) we applied a GeSn virtual substrate (VS) on Si (001) with a Sn content of 4.5 %, to produce s-Ge LEDs. The LED stack was grown by molecular beam epitaxy. Electroluminescence investigations of the s-Ge LED show a main direct Ge peak and a minor peak at lower energy, which is formed by the GeSn-VS and/or the s-Ge indirect transition. The main s-Ge peak is red-shifted as compared to the Ge peak of an unstrained 100 nm thick reference Ge LED grown on Ge-VS. At a temperature of T = 80 K the increased tensile strain, produced by the GeSn-VS, causes a red shift of the direct Ge peak from 809 meV to 745 and 769 meV, namely for the s-Ge LED with a 100 and 200 nm thick active layer. At T = 300 K the direct Ge peak is shifted from 777 meV of the reference Ge LED to 725 meV (for 100 nm) and 743 meV (for 200 nm). The peak positions do not differ much between the 50 and 100 nm thick s-Ge LEDs. The intensities of the direct Ge peak increase with the s-Ge layer thickness. Moreover, the intensity of the 100 nm thick s-Ge is found to be larger than that of the 100 nm thick reference Ge LED.

10108-14, Session 3

Laser and transistor material on Si substrate

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Silicon photonics requires material which is compatible with Si platform. Such a material in the best case should be processed directly on Si and should be efficient light emitter as well. This is narrowing the selection of conventional optical materials. We study Ge as a potential material for fast transistors and light emitters grown on Si substrate. Through originally indirect nature Ge turns into direct bandgap semiconductor under only ~1.55 % biaxial tensile strain according to 32-band k*p model. The strain is induced by growing Ge on an InGaAs buffer layer with variable In content. Besides that tensile strain boosts hole mobility making Ge valuable tunnel field-effect transistor material. Optical interconnects is desired for future processors, so Ge has benefit both for electronic and photonic parts. The strain is induced by growing Ge on an InGaAs buffer layer with variable In content. This designs energy diagram of semiconductor for future application: transistor and light emitter. Precise control of Ge energy bands is performed by photoreflectance and photoluminescence study of the material. Photoreflectance measurements provide precise values of transitions from both ? and L valleys with light and heavy hole splitting. Photoluminescence measurements provide energy gap value and photonic efficiency of the material. Both methods indicated bending of the bands with increase of tensile strain to the lower energy values in concordance with the calculated values of the band energies.

10108-48, Session 3

New experimental evidence for nature of the band gap of GeSn alloys

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To harness the advanced fabrication capabilities and high yields of the electronics industry for photonics, monolithic growth and CMOS compatibility are required. One promising candidate which fulfils these conditions is GeSn. Introducing Sn lowers the energy of the direct ? valley relative to the indirect L valley. The movement of the conduction band valleys with Sn concentration is critical for the design of efficient devices; however, a large discrepancy exists in the literature for the Sn concentration at which GeSn becomes a direct band gap. We investigate the bandgap character of GeSn using hydrostatic pressure which reversibility modifies the bandstructure. In this work we determine the movement of the band-edge under pressure using photocurrent measurements. For a pure Ge sample, the movement of the band-edge is dominated by the indirect L valley with a measured pressure coefficient of 4.26±0.05 meV/kbar. With increasing Sn concentration there is evidence of band mixing effects, with values of 9.4±0.3 meV/kbar and 11.1±0.2 meV/kbar measured for 6% and 8% Sn samples. For a 10% Sn sample the pressure coefficient of 13±0.5 meV/kbar is close to the movement of the direct bandgap of Ge, indicating predominately direct ?-like character for this GeSn alloy. This further suggests a gradual transition from indirect to direct like behaviour in the alloy as also evidenced from theoretical calculations. The implications of this in terms of optimising device performance will be discussed in further detail at the conference.

10108-15, Session 4

Silicon photonic modulators for PAM transmissions *(Invited Paper)*

Sophie La Rochelle, Raphaël Dubé-Demers, Univ. Laval (Canada); Alexandre D. Simard, Ciena Corp. (Canada); Benoit Filion, TeraXion Inc. (Canada); David Patel, David V. Plant, McGill Univ. (Canada); Wei Shi, Univ. Laval (Canada)

To generate multi-level signals without an electrical digital-to-analog converter (DAC), we first propose a Mach-Zehnder modulator (MZM) with electrodes and phase shifters segmented in three parts to generate PAM-8. The design includes series push-pull depletion based PN-junctions and on chip 50 ohm terminations to reduce the number of RF connections and allow testing with microprobes. Modulation bandwidth was limited by the longest electrode with a measured S21 3-dB bandwidth above 35 GHz. The PAM 8 DAC with segment lengths of L, 2L and 4L where L = 500 ?m, achieved 38 GBd (115 Gbps) transmissions below the hard-decision forward error correction (FEC) threshold of 3.8 ? 10?3. BER detection was done after the application of a minimum mean square error equalizer (MMSE) with 50 taps.

Compared to MZM, modulating the small resonant cavities of micro-ring modulators consumes much less energy although ring resonators must be tuned and stabilized. We present a PAM-4 photonic DAC based on a cascade of two microrings. The large signal 3-dB bandwidth of a single micro-ring is 25 GHz and the efficiency of its thermal heaters is 23 W/GHz. Back-to-back transmission below FEC threshold is obtained up to 30 Gbaud (60 Gbits) with equalization (30 taps). The power consumption is evaluated below 100 fJ/bit including the thermal tuners responsible for half the power.

This work shows that silicon modulators with multiple electrodes can be

advantageously used to eliminate the need for high bandwidth electronic DAC in the generation of multilevel signals offering very high speed and low power consumption to meet the needs of short reach data interconnects.

10108-16, Session 4

Multi-dimensional modulation and self-beating direct detection for data center optical interconnects *(Invited Paper)*

David V. Plant, Mohamed Morsy-Osman, Mathieu Chagnon, McGill Univ. (Canada)

We review multi-dimensional modulation and self-beating direct detection for data center optical interconnects.

10108-17, Session 4

Accurate Performance Evaluation of Single-channel Silicon Optical Interconnects Operating in the Pulsed Regime

Jie You, Nicolae Coriolan Panoiu, Univ. College London (United Kingdom)

Optical interconnects made of silicon are viewed as emerging efficient solutions for addressing the communication bottlenecks that plague high-performance computing systems and big-data centers. Due to large index contrast and optical nonlinearity of silicon, waveguides and active devices based on silicon can be scaled down to sub-wavelength size, making silicon photonics an ideal platform towards integrated on-chip photonic circuits. In order for this potential to be fulfilled, one needs to understand the factors that affect the quality of optical signals propagating in silicon optical interconnects, namely the bit-error ratio (BER), as well as the relationship between the parameters characterizing the optical signal and the BER.

In this work, an accurate approach to calculate the BER in single-channel silicon optical interconnects utilizing arbitrarily-shaped pulsed signals is presented. The optical interconnects consist of either strip single-mode silicon photonic waveguides (Si-PhWs) or silicon photonic crystal (PhC) waveguides (Si-PhCWs), and are linked to a direct-detection receiver. The optical signal consists of a superposition of Gaussian pulses and white noise. The signal dynamics in the silicon waveguides is modelled using a modified nonlinear Schrodinger equation, whereas the Karhunen-Loeve series expansion method is employed to calculate the system BER. Our analysis reveals that in the case of the Si-PhWs the pulse width is the main parameter that determines the BER, whereas in the case of Si-PhCWs the BER is mostly affected by the waveguide properties via the pulse group-velocity. A good system performance is achieved in centimeter-long Si-PhWs whereas similar system performance is obtained using 100? and 200? shorter Si-PhCWs operating in the fast- and slow-light regimes, respectively.

10108-18, Session 4

High-density silicon photonics for next generation datacenter networking *(Invited Paper)*

Aaron J. Zilkie, Rockley Photonics (United States)

Data centers are projected to require 1,000 times more bandwidth and compute capacity over the next ten years in order to meet the growth anticipated from applications such as cloud computing and the 'internet of things'. Datacenter switch fabrics are currently implemented with dis-aggregated hardware using discreet electronic CMOS switch chips, optical transceivers, and line-cards with power-consuming high-speed RF traces. These are connected together in a multi-layer architecture which grows increasingly complex, expensive and power inefficient as the datacenter scales in size. Rockley Photonics' solution uses high-density and high-performance silicon photonics and electronics technologies to integrate packet processing, switching, backplane and transceiver functionalities into a fiber-in/fiber-out modular unit to create lower cost, lower power, highly scalable switch networks, aggregating the functional elements of the network within a single module. Such modules can be interconnected to make a switch fabric that scales to virtually any size.

We will present novel technologies that emphasize high-density integration of large amounts of data in a small chip area, low-power consumption, and high manufacturability. We will present silicon photonics WDM technologies designed to provide efficient OEO conversion and capable of high speeds and high bandwidth per fiber, which are complementary metal-oxide semiconductor (CMOS) drivable needing ≤2 V drive, and are manufacturable with high yields when integrated. Key aspects include integration of modulators, detectors, MUXs and DEMUXs with CMOS drivers and digital switch functions in close proximity, and eliminating the need for power-consuming high-speed RF connections and dramatically decreasing power consumption and increasing data density.

10108-19, Session 5

High-brightness lasers on silicon by beam combining *(Invited Paper)*

Eric J. Stanton, Alexander Spott, Nicolas Volet, Michael L. Davenport, John E. Bowers, Univ. of California, Santa Barbara (United States)

High-brightness lasers receive broad interest in fields such as spectroscopy, infrared countermeasures, free-space communication, and industrial manufacturing. Advancing integrated technologies for high-brightness lasers can increase the efficiency and decrease costs. Integration of a broad-band, multi-spectral laser is made possible by heterogeneously integrating multiple gain materials on one silicon substrate chip. A single multi-spectral output with high beam quality can be achieved by wavelength beam combining first within the gain bandwidth of each laser material and then coarsely to combine all spectral bands. The major challenge of this system is first to demonstrate heterogeneously integrated lasers spanning the near-infrared to the mid-infrared and to demonstrated low loss wavelength beam combining elements on chip to make power scaling feasible. In this presentation, we review our progress on multi-spectral lasers integrated on silicon for scaling brightness and discuss various waveguide material platforms for spanning the visible to the mid-IR. Recent work integrating 2.0-micron diode and 4.8-micron quantum cascade lasers on silicon demonstrates that integrated, multi-octave spectral beam combining is indeed possible. Low-loss integrated beam combining elements are also presented for both dense and coarse multiplexing. Finally, we compare spectral and coherent integrated beam combining by analyzing system architectures and applications for each.

10108-20, Session 5

Thermal stress in an optical silica fiber embedded (soldered) into Si

Ephraim Suhir, Sung Yi, Portland State Univ. (United States) and ERS Co. (United States)

Simple, easy-to-use and physically meaningful analytical theory-of-elasticity based stress model is suggested for the prediction of thermal stresses in a cylindrical tri-material body. The numerical example is carried out for the case when a metalized optical fiber is soldered into a Si chip (Si photonics technology). The developed model is applicable also to situations when a fiber is soldered into a ferrule, or is adhesively bonded into a capillary. The developed model is rather general and can be used when cylindrical

tri-material bodies comprised of dissimilar materials and experiencing temperature excursions are employed. It is concluded that the adequate bonding material (e.g., a "soft" Sn-Pb or a "hard" Au-Sn solder) should be selected and its thickness should be established, for low enough thermally induced stresses, based on the developed model. Future work will include calculations for different solders and their thicknesses; FEA based computations to make sure that analytical and FEA data are in good agreement; experimental evaluations of the stresses at failure.

10108-21, Session 5

Development of new MPPC with higher NIR sensitivity and wider dynamic range

Terumasa Nagano, Ryutaro Tsuchiya, Atsushi Ishida, Koei Yamamoto, Hamamatsu Photonics K.K. (Japan)

The Multi-Pixel Photon Counter (MPPC) is generally called silicon photomultiplier (SiPM), which is a promising candidate for use in automotive light detection and ranging (LIDAR). High near-infrared (NIR) sensitivity, wide dynamic range and very fast response are required. Dynamic range depends on the number of microcells and the recovery time, so an MPPC with a small microcell, such as 25 micron or less, is suitable. Photon detection efficiency (PDE) is determined by multiplication of the geometrical fill factor (FF), the quantum efficiency (QE) and the avalanche probability (AP). NIR sensitivity mainly depends on the thickness of the depletion layer, and an n-on-p structure is essential to inject electrons generated in the deep area into the avalanche region. Conventional MPPCs, which have a p-on-n structure, were developed for blue-enhanced sensitivity, so a commercially available MPPC with 25 micron microcells shows only 2.5% PDE at 905 nm wavelength. Our new NIR-enhanced MPPC with n-on-p structure has achieved 7% PDE at 905 nm. Applying process design improvements to reduce the dead area will make it possible to achieve 12% PDE. To increase NIR sensitivity further, improvement of the QE has been studied. Generally, the depletion region's thickness is inversely related to the QE and the AP, so the thickness is mainly limited by the AP. We will develop a back-illuminated MPPC that achieves 20% PDE by increasing absorption length using multiple reflections without compromising the AP, and significantly improving the FF at the same time due to the absence of a shielding structure.

10108-22, Session 5

Design of an 8-tap CMOS lock-in pixel with lateral electric field charge modulator for highly time-resolved imaging

Yuya Shirakawa, Min-Woong Seo, Keita Yasutomi, Keiichiro Kagawa, Nobukazu Teranishi, Shoji Kawahito, Shizuoka Univ. (Japan)

Recently, CMOS time-resolved imaging devices are expected to be used for scientific and medical applications. A fluorescence lifetime imaging microscopy (FLIM), which is a powerful analysis tool in fundamental physics as well as in the life science, is a typical application of the time-resolved imaging devices. For better time-resolution in the lock-in pixel design, the number of time-windows and resulting output taps is required to be as many as possible. In this report, we propose an 8-tap CMOS lock-in pixel with lateral electric field charge modulator (LEFM) and demonstrate the effectiveness by TCAD simulation. The proposed pixel makes possible to measure the highly time-resolved imaging with a high signal to noise ratio (SNR) and to observe various imaging of cells having different fluorescence lifetimes in real time.

The pixel consists of a pinned photodiode (PPD), eight storage diodes (SDs), eight sets of LEFM (TG1 to TG8), eight floating diffusion (FD) nodes which are connected to each individual in-pixel source follower (SF) amplifier. The main goals of the developed pixel are to detect the signals with multiple time-windows (TWs) per single frame, resulting in eight signals being stored in the SDs, and to improve the SNR. To achieve this, we have designed a special lock-in pixel structure with an optimization of potential profiles. A W-shaped pixel, whose naming comes from the cross-sectional potential shaped like the letter of "W", is formed by removing the small n-type doping layer (PUP: pull-up point) at the center in the PPD, and the signal charges flow along with the formed potential valley around the PUP. In addition to this, a charge-transfer assisting (CA) gate is also developed for increasing the full well capacity and it helps to transfer the charges to FD node from the SD. The designed eight-tap CMOS lock-in pixel with LEFM will be useful for scientific and medical applications based on real-time time-resolved imaging techniques.

10108-23, Session 6

Energy-efficient millimeter-wave generation using silicon photonics *(Invited Paper)*

Martijn J. R. Heck, Hakimeh Mohammadhosseini, Aarhus Univ. (Denmark)

Due to the exponential growth of the bandwidth requirement for wireless communication systems, new frequency bands need to be utilized. For future 5G wireless networks, frequencies of 30 GHz to 90 GHz are considered, while for satellite and aircraft communications the sub-terahertz frequencies are considered. However, with increasing millimeter-wave frequencies (30 GHz – 300 GHz), high-speed electronic solutions become energy-inefficient, and alternative solutions are required.

Photonics offers the bandwidth and a potentially seamless integration with the fiber-wireless technology (Fi-Wi) for 5G communications. Commercially available terahertz generators are often based on photonics, i.e., lasers, too. One particularly promising technique to generate the microwave or sub-terahertz signal is to use the comb generated by modulating a continuous-wave laser signal. By filtering two non-adjacent comb lines, a beat signal is generated that has a frequency that is an integer multiple of the electrical modulator driving signal. In this way, frequency multiplication is achieved using microwave photonics. Photodetectors and/or photomixers can then be used to convert the beat signal to a millimeter-wave. However, the energy-efficiency of these techniques – and how they compare to all-electronic solutions – has not been analyzed yet.

In this paper we will present this energy-efficiency analysis, based on a silicon photonics implementation. Silicon photonics has the potential to miniaturize such systems, for ubiquitous and low-cost implementation. Silicon-based modulators, however, are not ideal phase modulators, and simulation tools need to incorporate this. The regimes, in terms of signal power and frequency, where photonics compares favorably over electronics, will be discussed.

10108-24, Session 6

Miniature, low-cost, 200 mW, infrared thermal emitter sealed by wafer-level bonding

Kari Schjølberg-Henriksen, Jo Gjessing, Kari Anne H. Bakke, Sanja Hadzialic, Dag Wang, SINTEF (Norway)

Micro electro-mechanical system (MEMS)-based infrared thermal emitters are used in several commercial applications, including non-dispersive infrared detector gas analysis for greenhouse gas monitoring. Device packaging is commonly done on the individual die level, resulting in a high cost for the single component. We present a new thermal emitter with unrivalled low power consumption, packaged on the wafer level by Al-Al thermocompression bonding. This patented device sealing provides through-silicon conductors and enables direct surface mounting of the components.

Thermal emitters were fabricated on silicon-on-insulator (SOI) wafers. The active area of 0.2 ? 0.2 mm2 was situated on the device layer and released from the handle wafer by wet silicon etching. The active area was resistively heated. The cap sealing silicon wafers had cavities enclosing the emitter area and anti-reflective coating, optimized for lambda =3.5 µm. 80 µm wide Aluminium frames on SOI and cap wafers were bonded in vacuum at 500oC, applying a force of 60 kN for 1 hour. After bonding, the wafers were diced into individual chips and characterized.

Emission spectra by Fourier Transform Infrared Spectroscopy showed high emissivity in the wavelength range 3 – 10 µm at 35 mA driving current and 5.7 V bias, i.e. 200 mW power consumption. Characteristics were in good agreement with COMSOL simulations which indicated a source temperature of 800oC and thermal time constant below 5 ms. Thus, these devices have 75-85% reduction in power consumption, ~20 times increase in switching frequency, and 40 – 60% reduction in production cost compared to available, individually packaged devices.

10108-25, Session 6

CMOS-compatible optical AND, OR, and XOR gates using voltage-induced free-carrier dispersion and stimulated Raman scattering

Dusan Gostimirovic, Winnie N. Ye, Carleton Univ. (Canada)

With the impending end of transistor downscaling, new technologies are needed to drive the next generation of computing technology. Silicon photonics has shown its potential in highly integratabtle, high-speed, and low-cost optical networking and sensing devices with a minimal change in foundry processes. Although there is no optical transistor, the various nonlinear optical effects present in silicon can be used to create optical switching and logic devices that meet and exceed current operating metrics on speed, power consumption, thermal stability, cost, footprint, manufacturability, and scalability. In this study, we explore two microring-resonator based optical switching methods: voltage-induced free-carrier dispersion and stimulated Raman scattering -based Zeno switching. Each are used to perform scalable addition and subtraction, as well as the fundamental, standalone gate operations. The free- carrier based method uses a double ? shift approach to minimize the ring count and the otherwise high complexity and spatial footprint of previously reported designs. Furthermore, we study how reverse-biased PIN diodes and ion implantation can be integrated into the design to reduce silicon's ~450-ps free-carrier lifetime, and therefore increase the operating speed of the device. The Raman-based method, on the other hand, performs all-optically, with single-resonance Zeno switching. This type of switching enables parallel computations by WDM, which significantly enhances bandwidth density. We believe both of these new methods offer significant improvements to the scalability of optical logic through parallel processing and size reduction.

10108-26, Session 6

Ultra-fast secure communication with complex systems in classical channels: towards a physical one paid system

Valerio Mazzone, King Abdullah Univ. of Science and Technology (Saudi Arabia); Andrea Di Falco, Univ. of St. Andrews (United Kingdom); Andrea Fratalocchi, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Developing secure communications is a research area of growing interest. During the past years, several cryptographic schemes have been developed, with Quantum cryptography being a promising scheme due to the use of quantum effects, which make very difficult for an eavesdropper to intercept the communication. However, practical quantum key distribution methods have encountered several limitations; current experimental realizations, in fact, fail to scale up on long distances, as well as in providing unconditional security and speed comparable to classical optical communications channels.

Here we propose a new, low cost and ultra-fast cryptographic system based on a fully classical optical channel. Our cryptographic scheme exploits the complex synchronization of two different random systems (one on the side of the sender and another on the side of the receiver) to realize a "physical" one paid system.

The random medium is created by an optical chip fabricated through electron beam lithography on a Silicon On Insulator (SOI) substrate.

We present experiments with ps lasers and commercial fibers, showing the ultrafast distribution of a random key between two users (Alice and Bob), with absolute no possibility for a passive/active eavesdropper to intercept the communication. Remarkably, this system enables the same security of quantum cryptography, but with the use of a classical communication channel.

Our system exploits a unique synchronization that exists between two different random systems, and at such is extremely versatile and can enable safe communications among different users in standards telecommunications channels.

10108-27, Session 7

Group IV compounds and silicon nitride for multiplatform integrated photonics *(Invited Paper)*

Frederic Y. Gardes, Thalía Domínguez Bucio, Lorenzo Mastronardi, Nannicha Hattasan, Kasia M. Grabska, Univ. of Southampton (United Kingdom); Callum J. Littlejohns, Nanyang Technological Univ. (Singapore); Mehdi Banakar, Graham T. Reed, Goran Z. Mashanovich, Antoine F. J. Runge, Yohan Franz, Anna C. Peacock, Univ. of Southampton (United Kingdom)

Polycrystalline and crystalline germanium and silicon germanium compounds have been demonstrated to be excellent materials for the fabrication of integrated microsystems in complementary metal oxide semiconductor (CMOS), micro-electromechanical systems (MEMS) and photonics. Crystalline germanium or silicon-germanium on silicon or insulator are also desirable and preferred systems for applications in near infrared and mid-infrared photonic devices. For near infrared, silicon-germanium is crucial for the fabrication of light emitters, detectors and modulators using effects such as the quantum confined Stark effect or Franz Keldysh effect for electro absorption. In order to fabricate optical components and enable the confinement of light in the horizontal and vertical direction, the deposition of high quality crystalline Ge or SiGe on insulator and the possibility to tune the bandgap of SiGe is of utmost importance. Here we demonstrate a new process building block to obtain crystalline germanium and silicon-germanium on insulator of different composition using a single deposition process. We are also demonstrating the capability of depositing low temperature (<350 degrees C), low loss (<1dB/cm) silicon nitride with different silicon content, enabling a wide range of multilayer waveguiding schemes with non-linear capabilities.

10108-28, Session 7

Fano line-shapes optically-induced transparencies and anti-crossing effects in coupled ring-enhanced MZI-type devices *(Invited Paper)*

Iain F. Crowe, Joseph Lydiate, Thomas Catherall, The Univ. of Manchester (United Kingdom); Zhao Wang, Edgar Huante-Ceron, Andrew P. Knights, McMaster Univ.

(Canada); Matthew P. Halsall, The Univ. of Manchester (United Kingdom)

We describe novel coupled ring enhanced Mach Zehnder Interferometer (MZI) and Y-split junction type devices based on single mode optical waveguides, fabricated from 220nm silicon-on-insulator (SOI). With integrated heater elements positioned over both arms of the devices, and using electrical contact probes to achieve independent thermal tuning of either arm/ring, we are able to demonstrate precise control of the device transmission spectra going from symmetric (Lorentzian) resonance line-shapes to highly asymmetric (Fano) resonances with extremely high extinction ratios (~30dB) and greatly enhanced q-factor. We develop a simulation based on the transfer matrix method (TMM) to understand the origin of the Fano resonance in our devices and describe how they might find application in high speed optical modulators or for extremely sensitive differential refractive index sensing applications. We also describe a new type of device with an additional (central) drop-port between our coupled ring resonators (inside the MZI), the reflection spectra from which reveals optically induced transparency and anti-crossing like effects due to coherent interference between the rings, and we outline possible applications for this type of device.

10108-29, Session 7

TiO2-coated shifted Bragg grating in silicon-on-insulator platform as add-drop filter

Somnath Paul, Ismo Vartiainen, Matthieu Roussey, Toni Saastamoinen, Jani Tervo, Seppo Honkanen, Markku Kuittinen, Univ. of Eastern Finland (Finland)

We present a sidewall patterned shifted Bragg grating based on an add-drop filter in silicon-on-insulator platform with a coating of amorphous titanium dioxide. This particular waveguide grating is equivalent to two identical gratings written across either sides of a waveguide with a longitudinal offset of half of a period. The add-drop operation occurs on the basis of mode conversion due to shifted sidewall structure followed by mode splitting with asymmetric Y-junction. A signal launched through the wide arm (single mode) of an asymmetric Y-junction generates the fundamental mode at the stem of the Y-branch. First order mode is generated at the stem if the signal is launched through the narrow arm. Thus, an asymmetric Y-branch is used as a mode splitter fulfilling proper limiting condition for an adiabatic operation. A signal at the Bragg wavelength launched through the wide arm of asymmetric Y-junction generates fundamental mode at the stem. The fundamental mode converted to first order upon reflection from the shifted Bragg grating. The reflected mode couples into the narrow arm of the Y-junction. The bandwidth of the reflected signal depends on the grating strength. We used 80 nm grating amplitude for 800 nm wide waveguide. The height of the guiding layer is 220 nm. The TiO2 thickness is set to 180 nm. A reflection bandwidth of 2.2 nm with 14 dB extinction ratio is obtained at 1552.5 nm for 300 μm long grating. We further demonstrate the potential of TiO2 recoating with atomic layer deposition as a method of fine tuning the spectrum.

10108-30, Session 7

Fabrication tolerant flat-top interleavers

Matteo Cherchi, Fei Sun, Markku Kapulainen, Tapani Vehmas, Mikko Harjanne, Timo Aalto, VTT Technical Research Ctr. of Finland Ltd. (Finland)

Integrated circuits based on micron-scale silicon waveguides have the clear advantage of being tolerant to fabrication errors, thanks to the high mode confinement within the guiding core. Here we show how flat-top interleavers can be achieved on a micron-scale silicon photonics platform based on ring-loaded Mach-Zehnder Interferometers (MZIs), without the need for any thermal tuning. Robust designs are also guaranteed by resorting to Multi-Mode Interferometers (MMIs) as power splitters in both the MZIs and the ring resonators. A trade-off between in-band ripple and roll-off can be achieved by changing the ring splitting ratios. In particular rings with different finesse based on MMIs with 50:50, 72:28, and 85:15 splitting ratios have been designed, fabricated and successfully tested. In-band ripples as low as 0.2 dB and extinction ratios exceeding 15 dB have been measured from the fabricated samples. Repeatability of the performances from chip to chip and wafer to wafer is presented to show the tolerance of the devices to fabrication errors. Even though these particular devices have been designed for TE polarization only, polarization insensitive designs can be also achieved. All designs are based on strip waveguides and compact Euler-bends, leading to footprints in the order of 700 x 300 μm^2, also thanks to an optimized configuration. They can find applications as interleavers as such or as stages in cascades of N interleavers to achieve flat-top 1x2^N (de) multiplexers.

10108-31, Session 7

Analytical Model for the Analysis of the Electromagnetic Field in Grating Couplers

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This paper presents a novel analytical model for analysis of the electromagnetic field radiation in grating couplers as a periodic structure. This model can describe periodic structures ,such as grating couplers, with appropriate accuracy. The obtained field distribution of the grating coupler is interestingly a Jacobi theta function, which results in a sequence of Fourier series for particular angles, compatible with the Floquet-Bloch theory of periodic structures. The effect of the parameters on the radiation pattern is also investigated. The results of the proposed analytical model are compared to simulation results in 1550 nm. Besides the grating coupler as a periodic structure, this method can be used for any given periodic structure.

10108-32, Session 8

A high-efficiency low-noise signal amplification mechanism for Si photonic detectors *(Invited Paper)*

Yu-Hwa Lo, Iftikhar Ahmad Niaz, Univ. of California, San Diego (United States); Mohammad Abu Raihan Miah, Univ of California San Diego (United States) and Univ. of California, San Diego (United States); Yu-Hsin Liu, Univ. of California, San Diego (United States) and Univ of California San Diego (United States); David Hall, Univ of California San Diego (United States)

Recently we discovered a signal amplification mechanism to amplify photocurrent with high efficiency and low noise. Unlike conventional impact ionization used in avalanche photodetectors, the new amplification mechanism can produce high (>1000) gain with very low excess noise factor (<2 for Si) under very low bias voltage (3V). The device shows peculiar temperature characteristics, with superior gain and noise performance at room temperature than cryogenic temperature. The results suggest that the amplification mechanism is related closely to electron-phonon coupling, acting as a negative feedback mechanism to regulate the gain fluctuations. The new amplification mechanism offers a promising solution for light

detection for Si-photonics, imaging, and sensing. Both experimental results and theoretical analysis will be presented.

10108-33, Session 8

Silicon hybrid SPAD with high-NIR-sensitivity for TOF applications

Takashi Baba, Terumasa Nagano, Atsushi Ishida, Shunsuke Adachi, Shigeyuki Nakamura, Koei Yamamoto, Hamamatsu Photonics K.K. (Japan)

We developed a hybrid-structured SPAD sensor, comprised of a Multi-Pixel Photon Counter (MPPC) and ASIC, suitable for time-of-flight rangefinding applications such as automotive light detection and ranging (LIDAR). The MPPC, a sort of silicon photomultiplier, has good photon-counting ability and timing accuracy. Recently, we have developed a new type of MPPC that has extended sensitivity in the near infrared region, wide dynamic range, higher photon detection efficiency, and various format configurations (single channel, 1D and 2D). We also developed a dedicated front-end and timing measurement circuit.

The advantage of our approach using a single-channel MPPC instead of a single SPAD per channel is robustness against background events generated by thermal dark count in its Geiger-mode cell and high illuminance like sunlight. The threshold setting in the high-speed comparator can effectively distinguish the correlated photon event corresponding to the laser source from random background events. The time of arrival of the picked-up signal can be captured by on-chip time-to-digital converters (TDC).

One of the most beneficial points on our approach is to implement a 2D MPPC array image sensor whose pixel pitch is less than several hundred ?m. This configuration can results in a unique Geiger-mode image sensor that has high geometrical fill factor and wide dynamic range and detect multi-photon events per single channel. Currently, we are developing a back-illuminated MPPC array sensor.

These hybrid structure components can be integrated into compact modules aimed for various time-correlated single photon counting (TCSPC) measurement, especially for rangefinding applications.

10108-34, Session 8

Photonic-integrated circuits for multi-color laser engines in flow cytometry

Thomas Klos, TOPTICA Photonics AG (Germany); Jeremy Witzens, Sebastian Romero-García, Lehrstuhl für Integrierte Photonik, RWTH Aachen Univ. (Germany); Douwe H. Geuzebroek, Joost van Kerkhof, Edwin Klein, XiO Photonics B.V. (Netherlands); Martin Büscher, Jürgen Krieg, Miltenyi Biotec GmbH (Germany); Patrick Leisching, TOPTICA Photonics AG (Germany)

Photonic Integrated Circuits (PIC) will change the fundamental paradigms for the design of multi-color laser engines for life science. Exemplified with flow cytometry (FCM), integrated optical technology for visible wavelengths will be shown to open a new spectrum of possibilities to control mode size, the number of output spots and even complex illumination patterns generated by interferometry. Integration of additional optical functions such as variable optical attenuation or fast shutters adds value to the PIC.

TOPTICA is demonstrating the integration of PICs in present laser architectures [1] that overcomes the need of fiber input delivery. Multiple wavelengths (405nm, 488nm, 561nm, 640nm) are coupled free space into the chip, leveraging its beam steering CoolAC technology for automatic realignment. Once in the waveguide, the light can be redirected and shaped to a desired output pattern and pitch, reducing the need of discrete optical components. We will discuss generation of adjustable fringe patterns by using broadband splitters and phase tuner arrays. Furthermore, we will analyze the advantages of various building blocks in PIC technology over present macroscopic methods.

As a member of the EU project PIX4Life [2], TOPTICA and its partners [3,4,5] intend to pave the way for photonic integrated circuits in life science applications. The innovative combination with a PIC will allow for a significantly more robust design, which in turn enables faster and more sensitive analysis. An outlook to achieve a fully integrated photonics package for FCM applications will be presented.

[1]http://www.toptica.com/products/multi_color_systems.html

[2]Grant Agreement No 688519 - http://pix4life.eu

[3]http://www.xiophotonics.com

[4]http://www.iph.rwth-aachen.de

[5]http://www.miltenyibiotec.com

10108-35, Session 8

High-Q resonance near-zero-wave vector in photonic crystal slab for label-free sensing

Yonghao Liu, Shuling Wang, Weidong Zhou, Yuze A. Sun, The Univ. of Texas at Arlington (United States)

Optical label-free sensing can detect small changes of refractive index (RI), which can be used for biochemical molecular detection, drug screening and gas detection. Approaching lower detection limit in RI sensing can be achieved by increasing the quality factor (Q) and the spectral sensitivity (S). Localized photonic crystal cavities can achieve very high-Q but typically have small-S because of small overlap between the optical field and the analyte. Surface plasmon resonance sensors can achieve high-S but suffer from low-Q due to strong absorption in metal. We report experimental result of RI sensing with high-Q for the singly degenerate mode in photonic crystal slab (PCS) when the incident beam is close to normal incidence (wave vector $k \approx 0$). Q = 3x10^4 was measured with high extinction ratio (ER > 10 dB) for the PCS in air. We demonstrated such singly degenerate Fano resonance can achieve lower detection limit for bulk liquid sensing. Q = 1.7x10^4 and spectral sensitivity of 98nm/RIU were measured in liquid for the PCS and a detection limit of 10^-5 RIU were achieved with our device. In theory, the Q of the singly degenerate mode will diverge to infinity when k approaches zero but not equal to zero. In real case, the Q will be limited by surface roughness, nonuniformities and material absorption such as water in our work. The high-Q for the singly degenerate mode close to normal incidence ($k \approx 0$) with relatively high-S is very promising to achieve lower detection limit for RI sensing.

10108-36, Session 8

Ultra-sensitive silicon-photonic on-chip sensor using microfabrication technology

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We propose a novel design of MZI based liquid sensor. The MZI is constructed using a silicon-thin waveguide with cross-sectional area equals 2 μm*50nm on a silicon dioxide (SOI). This waveguide can be easily fabricated using standard mask micro technology and simple etching process. Due to the fact of having such 50 nm height only, the mode profile is not confined inside the waveguide enabling the structure to highly sensitive to any change in the cladding media. Accordingly, the sensitivity of this structure is more sensitive than the conventional silicon photonic waveguide with few hundreds of nanometers heights. This structure lends itself for cheap and effective sensing systems. We introduced a Mach Zhender interferometer (MZI) configuration based on this waveguide structure to validate its performance.

The sensitivity of the optical structure was measured to be 20000 nm/

RIU with FOM (i.e. represents the overall performance) equals 400 for arm length of 215 μm. Such values out perform any other MZI photonic based sensor. Such design is characterized by its ability to be used in other optical applications as well like optical modulators in which it can increases the modulation index (extinction ratio) ultimately as compared to conventional silicon single mode based MZI structures with 200 nm height.

10108-37, Session 9

Ge-rich SiGe waveguides for mid-infrared photonics *(Invited Paper)*

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The extension of silicon photonics towards the mid infrared (mid-IR) spectral range has recently attracted a lot of attention. The development of photonic devices operating at these wavelengths is crucial for many applications including environmental and chemical sensing, astronomy and medicine.

Recent works regarding the development of Ge-rich SiGe waveguides on graded buffer layers will be presented. It will be shown that these waveguides demonstrate low loss and strong mode confinement for a large range of wavelengths and that they have a good potential for being a major building block of mid-infrared photonic integrated circuits.

10108-38, Session 9

Silicon-based GeSn photodetector and light emitter towards mid-Infrared applications *(Invited Paper)*

Shui-Qing Yu, Univ. of Arkansas (United States)

Silicon-based optoelectronic devices have long been desired owing to the possibility of monolithic integration of photonics with high-speed Si electronics and the aspiration of broadening the reach of Si technology by expanding its functionalities well beyond electronics. To overcome the intrinsic problem of bandgap indirectness in the group-IV semiconductors such as Si and Ge, a new group-IV based material, GeSn alloy, has attracted increasing interests. Recently, a direct bandgap GeSn has been reported and GeSn-based laser has been demonstrated, indicating the great potential of the GeSn technique. Moreover, the narrowed bandgap of GeSn extends the device operating range into the mid-infrared, which is desired for wide-ranging applications in the fields of optical interconnects, et al.

In this work, the following aspects have been discussed: firstly, the material growth of GeSn by commercially available chemical vapor deposition (CVD) system. Secondly, GeSn-based photodetectors, light emitting diodes (LEDs), and optically pumped laser have been systematically investigated. These devices operate in the wavelength range beyond 2 ?m.

10108-39, Session 9

Mid-infrared SOI micro-ring modulator operating at 2.02um

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Active SOI devices designed for mid-infrared operation beyond 1.55 μm boast a larger refractive index shift from carrier modulation due to the ?2 dependence found in the plasma-dispersion relations. Compared with carrier modulation-based devices designed for a wavelength of 1.55 μm, electro-refraction is increased by a factor of approximately 1.7 implying higher modulation efficiency and reduced capacitance for a given junction doping profile. The change in absorption with free-carrier modulation is similarly increased implying decreased resonator quality factor and a subsequent increase in modulation speed. We demonstrate here mid-infrared micro-ring resonator modulators on SOI. The modulator design is supported by experimental determination of intrinsic and doping induced loss; and the determination of bend loss for micron–scale 90o curves. The modulators have a radius of 10 μm and a waveguide cross-section of 220x600 nm with a 90 nm slab height. Preliminary DC measurements show an extinction ratio of >7 dB when the devices are driven with a Vpp of 1.5 V (from 0V to 1.5V forward-biased) for a wavelength of 2.02 μm. The development of a complete optical link is described using these ring modulators and previously described silicon based defect-enhanced detectors.

10108-40, Session 9

Subwavelength Si photonics for near- and mid-infrared applications *(Invited Paper)*

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We report our advances in development of subwavelength engineered silicon photonic devices for near- and mid-infrared applications. By periodically patterning Si with a pitch small enough to suppress diffraction, we synthesize an effective photonic medium with refractive index between those of Si and the cladding material. This technique releases new degrees of freedom in engineering of light-matter interaction, chromatic dispersion and light propagation in Si photonic waveguides. We present an overview of our recent results in the realization of novel devices including filters and waveguides for near- and mid-infrared wavelength range.

10108-42, Session 10

Improvement of sidewall roughness of sub-micron silicon-on-insulator waveguides for low-loss on-chip links

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Scientifique (France) and CEA-LETI (France); Corrado Sciancalepore, CEA-LETI (France) and MINATEC (France) and Commissariat à l'Énergie Atomique (France); Camille Petit-Etienne, Univ. Grenoble Alpes (France) and Lab. des Technologies de La Microélectronique, Ctr. National de la Recherche Scientifique (France) and CEA-LETI (France)

Silicon-on-insulator (SOI) has been a very successful platform for small-footprint Si-based photonic integrated circuits (Si-PICs).It offers the potentiality to co-integrate both optical (active and passive) and electrical components on the same substrate. Moreover, the high-refractive index contrast in Si/SiO2 waveguides allows a high confinement of the light and thus the use of sub-micron photonic wires, thus permitting the design of compact optical circuits. However, when downscaling waveguides to sub-micron dimensions, propagation losses become dominated by sidewall roughness scattering often generated during the waveguide patterning process. In the present work, we present the dependence of waveguide opto-geometric parameters (dimension, bending, cross-section), as well as the impact of the patterning processes on such scattering losses. Sub-micron SOI waveguides are fabricated by inductively coupled plasma reactive ion etching. The sidewalls roughness parameters, amplitude and correlation length are evaluated after processing by the fitting of power spectrum densities obtained from CD-SEM measurements. Roughness data are correlated to transmission losses measured on an optical test bench. Two masking strategies (photoresist and SiO2 masks) are evaluated for the optimization of the sidewalls roughness. Several smoothening processes are compared to further improve the roughness: thermal oxidation with different thicknesses and hydrogen annealing at different temperatures. The results are then compared to 3-D FDTD electromagnetic modeling. Preliminary results indicate the beneficial impact of SiO2 mask patterning and thick thermal oxidation on roughness, resulting in a line-edge roughness of 2.5 nm, thus paving the way to Si single-mode photonic wire featuring optical losses below 1 dB/cm.

10108-43, Session 10

Towards autonomous testing of photonic integrated circuits

Milan M. Milosevic, Xia Chen, Dave J. Thomson, Graham T. Reed, Univ. of Southampton (United Kingdom)

Silicon photonics has been pioneered as a material platform for thirty years with broad academic and industrial efforts worldwide to realise next generation datacom functionality in an optical format at low cost. A crucial component of any large scale manufacturing line is the development of autonomous testing at the wafer scale. Such a system will provide a possibility of coupling of light into a photonic circuit at arbitrary positions of that circuit in order to test individual photonic components. All proposed wafer scale testing of photonic systems to date are based upon a single fixed input coupler and a single fixed output coupler, or on grating couplers formed on the end of fibres. The former approach only facilitates testing of the entire photonic circuit thus lacking the capability of testing individual components, while using the latter approach causes rapid degradation of grating and fibre-end face due to frequent physical contact to device under test thus limiting the system lifetime and reliability.

The work presented in this paper offers a solution through the fabrication of grating couplers in silicon-on-insulator platform via ion implantation. The grating is subsequently erased after testing using fibre based laser annealing without affecting the optical performance of actual photonic circuit. Experimental results show a possibility for the realisation of low loss and compact solutions which may revolutionise photonic wafer-scale testing systems. The process is CMOS compatible and can be implemented in other platforms to realise more complex systems such as multilayer photonics or programmable optical circuits.

10108-44, Session 10

Passive photonic components and germanium contacts for a 200mm germanium-on-insulator photonic platform

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Germanium-On-Insulator based photonics is a promising technological platform. As part of the initial development of a germanium photonic platform, optical losses in passive structures and electrical injection for active components have been studied on Germanium-On-Insulator (GeOI) substrates fabricated using Smart-Cut™ technology [1]. The low threading dislocation density of the germanium (Ge) film is expected to reduce unwanted carrier recombination leading to improved performance of the passive and active Ge components.

Fiber-couplers and 500nm square waveguides have been fabricated from 200-mm GeOI substrates allowing optical loss measurements in the TM mode at a wavelength of 2.3μm. Propagation losses were evaluated at 1.5dB/cm. Circular-shaped radius bends and evanescent couplers/splitters have also been simulated, fabricated and characterized to determine the bending losses and the coupling coefficient for ring resonators. Furthermore, innovative bend shapes showed lower bending losses than those with circular-shaped radii, which would allow higher component densities.

Finally, the electrical injection is of prime importance in fabricating efficient active components on GeOI. For this, the rectifying or ohmic behavior at the metal-semiconductor contact and its dependence as a function of the Ge doping or metal type has to be precisely known. In particular, we examined the challenging question of the contact resistance between metal and n-type Ge. A study has been conducted using Transfer Length Model (TLM) structures to determine the most suitable metal to contact n-doped and p-doped germanium.

[1] Reboud, V. et al. Proc. SPIE 9367 (2015).

[2] Kang, J. et al. Opt. Express 24, 11855-11864 (2016).

10108-45, Session 10

Integration and modeling of photonic devices suitable for high-performance computing and data-center applications

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Silicon photonic technology is becoming a real solution to address the increasing needs of HPC (High Performance Computing) systems and

datacenters. Going to technology level feasibility to real circuit design need to increase process maturity and require device integration into EDA tool, including device model.

In this work we report an optimization of a 200 mm silicon photonic platform [1] integrating a set of devices dedicated on HPC applications. The main component is a PiN micro-ring modulator [2]. Passive ring devices extension ratio reaches -40dB while Q factor is around 40000. Active tuning through heating section is investigated

Using either doped silicon or metal resistors. Both solution are considered and compared. Germanium photodetector featuring intrinsic responsivity higher than 0.8 A/W is also integrated. Optimized silicon patterning module to device passive device and optical routing is also available. Two AlCu metal levels are used for electrical routing purpose but also for decoupling capacitor.

This technology is supported by a dedicated process design kit (PDK) compatible with conventional CMOS EDA tools. The PDK includes optical device models that will be described and compared with experimental results. A focus will be done on the PiN micro-ring modulator models which covering a wide range of geometries. DC mode and RF behaviors are supported. At the end, simulation of a full WDM transceiver system using these models will be done and compared to experimental results.

10108-11, Session 11

Integrating III-V quantum dot lasers on silicon substrates for silicon photonics *(Invited Paper)*

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Silicon is one of the most important semiconductor materials. Although it has been the mainstays for modern electronics, it is not widely used for light emitting sources because bulk silicon is an inefficient emitter, a result of indirect bandgap. Direct epitaxial growth of III-V nanostructures on silicon substrates is one of the most promising candidates for realizing photonic devices on a silicon platform. In this presentation, the growth of III-V quantum dots - semiconductor nanosized crystal - on Si substrates and their applications in communications will be discussed. I will describe new development in the growth techniques developed at University College London for the formation of III-V buffer layers grown directly on Ge, Si and Ge/Si substrates by Molecular Beam Epitaxy (MBE). We demonstrated the first practical silicon-based laser diode with pulsed (cw) lasing up to 120 oC (75 oC), with an ultra-low cw threshold current density 62.5 A/cm2, a high output power exceeding 105 mW at RT, and a long extrapolated lifetime of over 100,158 hours [Nat. Photonics 10, 307-311(2016)]. These results are a major step towards silicon-based photonics and photonic-electronic integration, and provide a route towards cost-effective monolithic integration of III-V devices on Si platform.

10108-46, Session 11

High-quality and homogeneous 200-mm GeOI wafers processed for high strain induction in Ge

Alban Gassenq, CEA-LETI (France); Samuel Tardif, Kevin Guilloy, Nicolas Pauc, Mathieu Bertrand, CEA-INAC (France); Jean-Michel Hartmann, Julie Widiez, Johan Rothman, ROUCHON Denis, CEA-LETI (France); Yann-Michel Niquet, Ivan Duchemin, CEA-INAC (France); Jérôme Faist, ETH Zürich (Switzerland); Thomas Zabel, Hans C. Sigg, Paul Scherrer Institut (Switzerland); Francois Rieutord, CEA-INAC (France); Alexei Tchelnokov, Vincent Reboud, CEA-LETI (France); Vincent Calvo, CEA-INAC (France)

Ge under high tensile strain is very attractive as active gain medium of mid infra-red lasers fully compatible with CMOS technologies. In order to overcome mechanical failure under high stress, 200-mm Germanium-On-Insulator wafers were fabricated using the SmartCutTM approach [1], allowing us to demonstrate the highest strain never reported so far in thick Ge layers [2,3]. Since very high strain can be now induced in Ge micro-bridges, highly strained Ge cavities are currently being developed [4]. In this work, we present our investigation of the strain homogeneity in our GeOI wafers and report recent improvements concerning the design and processing of our Ge cavities. Using Laue micro-diffraction measurements performed at line BM32 of the ESRF synchrotron, a strain homogeneity of 0.163 ± 0.003% at the micro-scale is demonstrated, illustrating the high crystallographic quality of our GeOI wafers. We have otherwise shown that the strain and the thermal management is highly dependent on the bridge geometry. Depending on the chosen process flow, the Ge can be suspended or landed on Si or SiO2. Thanks to landed micro-bridge, we have performed PL measurements up to 3.6% of strain showing an improvement in the emitted signal with strain. This work shows the high potential of Ge micro-bridges cavities processed in 200-mm GeOI wafers for laser applications.

[1] V. Reboud, et al. Proc.SPIE 9752(2016)

[2] A. Gassenq, et al. Appl. Phys. Lett. 106(2016)

[3] A. Gassenq, et al. Appl. Phys. Lett. 107(2015)

[4] J. Petykiewicz, et al. Nano. Lett. 16(2016)

10108-47, Session 11

Optical study of strain-free GeSn nanowires

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Combination of group IV materials for sufficient grown quality and Sn content for enhancing optical properties is one of the solutions for real Si integration. Ge has a prominent role because its conduction band minimum at the ?-point of the Brillouin zone is located only ?0.14 meV above the fourfold degenerate indirect L-valley. One of the ways to achieve a direct-bandgap material is to incorporate Sn atoms into a Ge lattice, which primarily reduces the gap at the ?-point. Here we report a liquid injection chemical vapor deposition of GeSn nanowires on Si substrate from the Au seeds with up to 9% Sn content in the nanowire array which is higher nanowires Sn content than previously reported. Sn was uniformly distributed throughout the Ge nanowire lattice, as determined by atomic resolution energy electron loss spectroscopy, with no metallic Sn segregation or precipitation at the surface or within the bulk of the nanowires. Energy gap was studied by temperature dependent photoluminescence and show emission more than at 2.4um at 77K, which is at crossing point of direct-indirect transition of GeSn.

10108-49, Session 11

Modeling, design, and characterization of an SOI-based optical integrating loop

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Optical integrators are basic components in signal processing, filters, pulse shapers, or in more sophisticated applications such as feedback control loops, all-optic A/D converters, and asynchronous sigma-delta modulators.

In previous works an incoherent optical integrator based on an active loop containing a semiconductor optical amplifier (SOA) and a wavelength converter was demonstrated [1]. In this paper we present modeling, design,

and measurements of a novel integrated version of a non-interferometric integrator based on an active loop containing an externally connected SOA.

The design of the integrated parts was done using Klayout software. This loop contains of an SOA as a gain element, an optical isolator, a bandpass filter. The electron-beam lithography is performed on an SOI wafer and all the Si waveguides are designed to have dimensions of 500nm?220nm. The optical isolator consists of two resonance-matched filters: one notch filter (NF) and one add-drop filter (ADF). This device acts like a diode, allowing propagation in one direction. A titanium heater allows tuning of the NF resonance to match that of the ADF.

The optical isolator and bandpass filter were designed based on silicon micro ring resonators. The couplers are 2?2 adiabatic couplers with a coupling ratio of 0.5. The coupling coefficient between the ring resonators in the bandpass filters is the same and the radius of the ring resonators are 10 ?m. By connecting an add-drop filter and an all pass filter in series, an OI was designed while both ring resonators had a radius of 5 ?m.

1. P. Costanzo-Caso, Y. Jin, S. Granieri, and A. Siahmakoun, "Optical Leaky Integrator with Inverted and Non-inverted Accumulation," Microwave and Opt. Tech. Lett., 53, 2034-2037(2011).

10108-51, Session PWed

Bandwidth and center wavelength tunable micro-ring optical filter with Vernier effect by four spectrum combination

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A new bandwidth and center tunable micro-ring optical filter structure (matrix structure) which can realize a broad range of bandwidth and center wavelength is presented. It combines the drop transmission of two microring group, each of which locates at the corner of the matrix and consists two units (A unit can be any kind of combination of microrings). We designed two filters based on this structure, including a four rings and a six rings filter. The four rings filter consists of four equal units with single ring in each unit while the six rings consists of two equal single ring units and two equal double rings (cascade) units. In the unit of the double ring, the radius of two rings is designed to be proportional thus the FSR will increase due to vernier effect, which means the bandwidth range is also expanded. Both simulation and experiment show the high performance of this structure. In the experiment of the four rings filter, the bandwidth range can be regulated from 0.6nm to 2.8nm (the interval is 0.2nm) with the insertion loss from 1.26dB to 7.08dB and the extinction ratio from 17.5dB to 12dB. Also, the change of center wavelength can reach 2nm under 71.11mW electrical power (heating power). For the six rings filter, the bandwidth range reaches more than 15nm based on the Vernier effect.

10108-52, Session PWed

Dynamic routing control of Si optical interconnects

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While optical interconnects is expected in the near future to provide the most definitive answer to the current bottleneck in further scale down of the electrical interconnects in VLSI circuits by replacing electrical interconnects altogether, it is currently hindered by the fact that traditional optical interconnect would usually require waveguides that are at least an order of magnitude larger than its electrical interconnect counterpart with a separation distance of few microns to avoid undesirable coupling. Plasmonics offer a solution to the waveguide dimension problem as the guiding mechanism in plasmonic waveguide depends on the coupling between electrons and photons and allow for using waveguides with sub-wavelength dimensions on the expense of greater losses. By using doped silicon as the material of choice, we can acquire plasmonic mode in the near and mid infrared. In this paper we use slot waveguides with both doped and intrinsic silicon material in building interconnects and investigate their effectiveness as optical interconnects with dimensions match their electric counterparts. For the doped silicon the modes are plasmonic and allow for excellent performance in transmission through 90 degree bends and near perfect power splitting through T-junctions. We investigate the propagation losses of both dielectric and plasmonic slot waveguides. Then we investigate how we can dynamically control and switch on and off part of the optical interconnect network. This is achieved by manipulating the number of free carriers through light and/or carrier injection. Hence provide an ultrafast switching and routing solution for optical interconnect with dimensions in the same order of magnitude as current electrical interconnects dimension

10108-54, Session PWed

Diffusion-doped plasma dispersion silicon modulators

Vadivukkarasi Jeyaselvan, Shankar Kumar Selvaraja, Indian Institute of Science (India)

We present a diffusion doping based plasma dispersion optical modulator in Silicon-On-Insulator platform. To the best of our knowledge this is the first demonstration of a diffusion-doped (Boron and Phosphorus) modulator in a compact Silicon waveguide. Unlike ion-implantation technique used for creating a doped region in modulators, diffusion doping does not create any structural damage to the device. However, it results in a graded, isotropic doping profile where lateral diffusion length of the dopants is a critical parameter. We use a micro-ring resonator and proximity doping with varying offset besides the waveguide to experimentally measure the lateral diffusion length. The lateral diffusion is characterized from the change in the Q factor and extinction of the ring resonator. Experimental measurement shows a lateral diffusion length of ~ 1400 nm in a 220 nm thick Si device layer, which agrees well with the theoretical calculation.

With the lateral dopant diffusion length, we have designed and fabricated a 1 mm long pn MZI modulator. Fabrication was done using a combination of optical and e-beam lithography. The MZI waveguides were defined with 160 nm etch in a 220 nm device layer with a waveguide width of 450 nm. As an initial demonstration, we show plasma dispersion based spectral blue shift of 1.5 nm with a reverse-bias voltage of 5 V.

10108-55, Session PWed

Design and implementation of a 90-degree optical-hybrid-based adaptive polarization controller in silicon photonics integrated circuit

Anamika Singh, Rakesh Ashok, Shivangi Chugh, Shalabh Gupta, Indian Institute of Technology Bombay (India)

The problem of polarization mixing becomes pronounced with enhanced data rate in coherent optical communication links. Mitigating the effect of such polarization impairments is one of the major challenges in polarization multiplexed optical communication systems. Stokes parameters, a measure of state of polarization, deviate from ideal values due to polarization mixing. For restoring the Stokes parameter to the ideal values a novel architecture using 90 degree hybrid is proposed in this work. The two parameters governing the state of polarization, electric field intensity and phase difference are to be corrected. These parameters of the received signal are

corrected using two independent feedback control loops. One of the loops rectifies the phase error between the two orthogonal polarization while the other nullifies the field intensity difference.

A 90° hybrid comprising of a 90° thermo-optic phase shifter and 3 dB couplers has been designed in 220 nm Silicon-On-Insulator (SOI) technology platform. The designed structure has been simulated in COMSOL Multiphysics. The feedback control loop is realized using MATLAB and VPI Transmission Maker. The simulations show promising results in terms of reduced insertion loss and enhanced extinction ratio.

10108-56, Session PWed

Design optimization of multilayer SOI spot-size converter

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We have carried out design optimization using detailed numerical analysis of a Si/SiO2 based spot-size converter (SSC) for efficient coupling between a Silicon (Si) nanowire (NW) and a conventional single-mode fiber (SMF). The spot-size converter is made of an evanescently coupled NW (having standard dimensions of 220nm x 500nm) and a Poly-Si multi-layer structure/ array, where the NW and the array can be phase-matched to transfer power from the NW to the array at the coupling length. The array in this SSC design consists of 17 identical single-moded Poly-Si waveguides of width 6 micrometers and material between these waveguides is SiO2. The coupling loss between this SSC and a single-mode fiber of radius 2 micrometers for TE mode at perfect alignment is only 0.08 dB which is one of the lowest reported so far using other types of SSC. Alignment tolerances between this SSC and the conventional SMF have also been discussed here. This design does not comprise of any tapered waveguides and therefore the fabrication is simpler compared to the generally used vertical tapers. The simulations have been carried out using an efficient algorithm based on H-field full-vectorial Finite Element method and the Least Squares Boundary Residual method. The fabrication of this SSC can be carried out using Plasma Enhanced Chemical Vapour deposition (PECVD) and Reactive Ion Etching (RIE). This newly proposed design can be useful in the solving the challenge of high packaging costs for the integrated photonic chips.

10108-57, Session PWed

Photonic crystal ring resonator: a promising device for a multitude of applications

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The area of integrated optics is getting matured by the advent of high resolution fabrication techniques in research and the well established routes of submicron electronics foundry. A 2D Photonic Crystal array on SOI platform having hexagonal periodicity with a ring defect incorporated along with two bus waveguides is conceptualised and realised in this paper for various applications in optical communication, sensing etc. The device is designed to work in the communication band of optical spectra with centre wavelength at 1550nm. The Photonic crystal is designed to have band gap of 1240nm-1600nm. The ring structure filters out a resonant wavelength from the spectrum carried to it through the line defect, where the resonated peak is determined by the effective ring radius. The hexagonal architecture enables more coupling length than a regular ring structure which helps in better intensity accumulation. The resonant peak exhibited at 1549nm in simulation, which is verified to be at 1543nm through optical characterisation. The variation is owing to the cumulative effect of various fabrication steps. Grating couplers with periodicity of 630nm and etch depth of 70nm is embedded on the same device layer along with tapered strip waveguides and 900 bends to facilitate i/p and o/p coupling of the Photonic Crystal Ring Resonator device. Optical characterisation of the fabricated device yielded good overlap with the predicted results by the simulation using commercial FDTD software. The device is also demonstrated by adding free standing micro cantilever structure by etching underneath BOX layer for deflection sensing or tuning applications.

10108-58, Session PWed

Bloch mode selection in silicon-based photonic crystal microring resonators

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We report experimental results of a novel method to select a subset of Bloch modes in a highly dispersive photonic crystal microring resonator (PhCR) on a silicon-on-insulator substrate.

PhCR has potential applications in optical signal processing and low-energy optical modulation. The periodic structure in the PhCR leads to strong slow-light dispersion near the photonic band-edge, which introduces Bloch modes yielding intensity beating mode patterns in the resonator. Because of the substantial difference in spatial intensity distribution for each Bloch mode, we expect to be able to preferentially select a subset of resonances by adjusting the position of the output coupling waveguides.

The PhCR used in this work has a photonic bandgap near 1515nm. At the resonances within the slow-light regime, a loaded quality factor of ~2100 was measured. The largest estimated group index is ~12 near the band-edge. When the output coupling waveguide is positioned at an angle of 90 degrees with respect to the input coupling waveguide to the PhCR, only a subset of resonances (the even modes) has been selected. However, when the output coupling waveguide is positioned at an angle of 180 degrees with respect to the input coupling waveguide to the PhCR, all resonances have been out-coupled to the drop-port. The contrast between the output transmission for the odd modes at the drop-ports at 90 and 180 degrees is ~6dB, while the contrast for the even modes is less than 1.5dB. This approach could be useful in on-chip optical devices such as multiplexers and add-drop filters.

10108-59, Session PWed

Operational bandwidth of on-chip silicon optical buffers based on microring resonators in an all-pass filter configuration

Bruna Paredes, Anatol Khilo, Marcus S. Dahlem, Masdar Institute of Science & Technology (United Arab Emirates)

On-chip optical buffers are important building blocks in photonic integrated circuits, and can be implemented using delay lines based on microring resonators. In these structures, the group delay is enhanced by the resonant nature of the devices, where larger quality factors lead to larger delays. However, the operational bandwidth, which limits the bit rate of a data stream delayed without errors, is inversely proportional to the quality factor. This trade-off can be overcome by cascading several high-quality-factor microring resonators in an all-pass filter configuration, where the resonant frequencies are slightly detuned from ring to ring. In this work, we study a broadband compact optical buffer for operation in the C-band, designed in a 220 nm-thick silicon-on-insulator platform, formed by cascading 1000 10 μm-radius microring resonators. The precise control of the resonant frequency of each microring requires nm-scale dimensional fabrication

control of its waveguide width and height, and ring radius. While the width and radius have a Gaussian-like probability distribution resulting from fabrication, the waveguide height is continuous and approximately linear over distances much smaller than the typical wafer non-uniformity characteristic lengths. Pre-corrections for the wafer height variations can be made; however, we show that this local adiabatic height variation can also be used towards enabling the desired ring-to-ring detuning needed for increasing the bandwidth. Through 3D FDTD computations, we investigate the device bandwidth resulting from variations in the different dimensional parameters (width, height and radius), and compare it to measurement results from structures fabricated using 248 nm deep UV lithography.

10108-60, Session PWed

Electro-optic modulator with low-driving voltage and high-speed operation based on polymer-filled silicon one-dimensional photonic crystal slotted waveguide

Chi-Jui Chung, The Univ. of Texas at Austin (United States); Harish Subbaraman, Omega Optics, Inc. (United States); Rui Wang, Zeyu Pan, Ray T. Chen, The Univ. of Texas at Austin (United States)

An electro-optics (EO) modulator which can be operated at low driving voltage and high speed based on an EO polymer infiltrated silicon one dimensional (1D) slotted photonic crystal waveguide (PCW) is proposed, fabricated, and experimentally tested. The slotted PCW features narrow silicon tooth connected to bulk silicon which greatly reduce the serial resistance so that RC delay is significantly reduced and the EO polymer poling efficiency is increased. Therefore, it can be operated at low driving and high speed while maintaining the slow light effect and the large optical volume mode overlap in the EO polymer filled slot. By taking advantage of the slow light effect in the slotted PCW(>10X), large EO coefficient of the EO polymer(r33=135pm/V), as well as the push-pull working configuration that doubles the phase shift, we realize a huge in-device EO coefficient so as to realize a high performance EO modulator. To minimize the insertion loss, the high efficiency strip-to-slot mode converters and group index tapers are also carefully designed to reduce the modal mismatch and Fresnel loss caused by slow light effect respectively. As a result, a nearly flat transmission over the entire guided mode spectrum and minimum insertion of -5dB is demonstrated. The proposed EO modulator shows the promising potential for high speed, low power, and high integration needs of future optical interconnect applications.

10108-61, Session PWed

Dynamic optical control of silicon nanoparticle scattering in the near- and mid-IR

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Localized Surface Plasmon Resonance (LSPR) that occurs in plasmonic nanoparticles due to interaction with electromagnetic waves at wavelengths larger than the nanoparticles themselves has been exploited in many application like solar cells, cancer treatment and spectroscopy due to the enhanced scattering and absorption cross sections that LSPR provides. Being able to control the resonance peaks of scattering in real time using light can be a valuable tool for sensing-related applications as well especially if it happens in the near and Mid-IR spectrum where most of the biological molecules can be sensed as such spectrum contains strong characteristic vibrational transitions of many important molecules . In the work presented here, we use silicon nanoparticles and increase the concentration of free excess carriers in the nanoparticles by light generation until the free carrier concentration is large enough to cause LSPR similar to what we get with nanoparticles made of Nobel metals. The LSPR generated by Si nanoparticles with high concentration of free carriers causes the resonance peak to happen in near and mid IR and depending on the level of carrier concentration as well as the refractive index of the surrounding environment which both can be changed dynamically in real time, we can control the scattering resonance peak characteristics and position as shown in our work. Fabrication of the Silicon nanoparticles is realized and carrier generation and scattering characterization is conducted and compared to the simulation results.

10109-1, Session 1

Low-loss characteristics of a multimode polymer optical circuit at 1.3-um wavelength on printed circuit board *(Invited Paper)*

Takeru Amano, AIST (Japan); Akihiro Noriki, AIST (Japan) and PETRA (Japan)

Optical interconnection is a promising solution to eliminate this bottleneck because of its high transmission rate, high bandwidth density, and low power consumption compared to conventional electrical wiring. A bandwidth breakthrough requires converting electrical and optical signals as closely as possible to large-scale integrated circuits. However, package-board interconnections with low wiring capacity in current hierarchical packaging configurations limit the bandwidth density of multi-channel optical interconnections. We propose an optical and electrical hybrid LSI package with high bandwidth of 2.4 Tb/s and parallel multi-mode optical links at 1.3 um using a polymer optical waveguide and our original optical I/O module.

We report a silicon based polymer optical circuit fabrication including waveguide, mirror and connector on electrical LSI package substrate. We also present about the propagation loss, bending loss and coupling loss at 1.3 um using a MMF and a Si photonics transmitter.

The propagation loss of the multimode silicone-based waveguide is 0.3 dB/cm at 1.3 um. We realized low propagation loss compared with epoxy-based waveguide at 1.3 um. The coupling loss of butt-coupling and mirror coupling from the polymer optical waveguide to the MMF is 0.4 dB and 1.2 dB, respectively. The excess coupling loss with a passive alignment of the connector was below 1 dB.

We also measure the optical characteristics of LSI package substrate using our multimode Si photonics transmitter integrated with vertical polymer waveguide. The characteristics of the insertion loss, tolerance and crosstalk are almost same as MMF input case due to same beam property.

10109-2, Session 1

Future of high-speed short-reach interconnects using clad-dielectric waveguide *(Invited Paper)*

Joon-Yeong Lee, Hail Song, KAIST (Korea, Republic of); Soon-Won Kwon, Silicon Works (Korea, Republic of); Hyeon-Min Bae, KAIST (Korea, Republic of)

The ever-increasing demand for bandwidth triggered by mobile and video Internet traffic requires advanced interconnect solutions satisfying functional and economic constraints. Optical solutions are generally believed to replace high-speed conductor-based interconnects even in short-reach links. However, the widespread use of optical communication systems in high-volume short-reach applications is yet to gain acceptance due to its high-cost components, high-precision manufacturing process requiring micron-level accuracy, and the sheer physical size of modules. Moreover, designs with a practical balance of performance/robustness/power consumption of optical devices erode the potential advantage of the optical fibres. This being the case, the E-TUBE proposes a new interconnect scheme suitable for next-generation high-speed I/O interfaces. The E-TUBE demonstrates an unprecedented level of performance in terms of bandwidth per carrier frequency, power and density without requiring a precision manufacturing process. The E-TUBE exhibits a frequency-independent loss-profile of <4dB/m and has >20-GHz bandwidth over the V band. A single-sideband signal transmission enabled by the inherent frequency response of the E-TUBE renders two-times data throughput without any physical overhead compared to conventional radio frequency communication technologies. Increased centre frequency accompanied by semiconductor technology scaling will result in the increase of wire density and throughput. In addition, frequency-independent loss-profile of the E-TUBE enables the adoption of advanced modulation schemes that improve the spectral efficiency without complex equalizers.

10109-3, Session 1

Optimization of optical losses in waveguide component manufacturing *(Invited Paper)*

Brandon W. Swatowski, Maynard G. Hyer, Debra A. Shepherd, Jon V. Degroot Jr., W. Ken Weidner, Dow Corning Corp. (United States)

Optical waveguides have long been a potential candidate for optical data routing for communications systems. Silicones have been shown to meet performance and reliability requirements needed for optical signal routing. We report on the development and optimization of key performance properties of multimode silicone polymer waveguides, manufactured for 850 nm optical propagation. These developments are based on photopatternable, mechanically flexible, low-loss, gradient index silicone waveguides. Cross sectional dimensional waveguide core sizes ranging from 40 μm x 40 μm to 60 μm x 60 μm are assessed with optical analysis of component loss values such as crossings and coupling between OM4 fiber and waveguide. Assessments of these values, led to optimization of waveguide size and lower total optical losses in the system. Methods of manufacture, preparation, and analysis are discussed in detail along with performance results.

10109-4, Session 1

Evaluation of hybrid polymers for high-precision manufacturing of 3D optical interconnects by two-photon absorption lithography *(Invited Paper)*

Arne Schleunitz, Jan J. Klein, micro resist technology GmbH (Germany); Alexander Krupp, Benedikt Bender, Ruth Houbertz, Multiphoton Optics GmbH (Germany); Gabi Grützner, micro resist technology GmbH (Germany)

The fabrication of optical interconnects (OI) has been widely investigated for optical circuit boards with low power consumption, high bandwidth, and at low cost. Typical manufacturing technologies involving optical polymers are UV lithography, UV molding, or laser-direct writing. However, these processes are two-dimensional and hence limited in creating 3D micro optical components. Furthermore, the employed polymers have to satisfy numerous requirements concerning their optical and processing properties (e.g. optical loss and temperature stability).

ORMOCER®-based optical hybrid polymers have been already successfully applied in industrial photonic applications such as wafer-level optics. Furthermore, they were particularly tailored to the fabrication method employed (e.g. UV lithography and UV molding). In recent years, their general compatibility to two-photon absorption (TPA) lithography as an innovative production method for direct manufacture of individual 3D photonic structures has been demonstrated. However, the performance of optical waveguides manufactured in hybrid polymers by means of TPA was not investigated in detail until now.

Here, we report on new hybrid polymer prototypes particularly tailored to match the TPA requirements. Aiming for OI manufacture, optical waveguides were created with arbitrary length depending on the writing field of the positioning stages. For example, waveguides with a length of 1 cm and diameters down to below 1 ?m were created for pitch adjustment of, e.g. 125 to 62.5 µm. The optical properties such as refractive-index profile and their long term stability were assessed. The results demonstrate that innovative hybrid polymers are promising candidates to manufacture polymeric optical systems down to the chip level.

10109-5, Session 1

Design and fabrication for graded-index core-tapered polymer waveguide for a coupler device of laser source and multimode fiber

Hoshihiko Toda, Takaaki Ishigure, Keio Univ. (Japan)

The operation speed of high-performance computers has increased dramatically over the last decades. For sustaining their growth, multimode fiber (MMF) links have been gradually deployed, and on-board interconnection is the next step. Polymer optical waveguides (POWs) have been expected as one of the key components for on-board interconnects: they are expected to connect the light source/ photo detector on-board and an MMF off-board.

As a unique fabrication method for POWs, we developed the Mosquito method to obtain graded index (GI) circular core polymer waveguides and confirmed their low propagation loss compared to conventional step-index (SI) core waveguides. However, the connection loss of the light source to waveguide, and the waveguide to an MMF is a concern: insertion of the polymer waveguide between the light source and MMF would increase the optical loss.

So, in this paper, a tapered GI core polymer waveguide is proposed for reducing the connection loss between the laser sources and fibers/ waveguides by inserting it between the source and MMF.

In the Mosquito method, a liquid core monomer is dispensed from a thin needle attached to a syringe into a cladding monomer, using a microdispenser. Hence, the core diameter is axially varied by changing the needle-scan velocity.

First, the optimum refractive index profiles in the tapered core are theoretically predicted using the BPM method. Next, the refractive index profile formed in the core during the Mosquito method is also estimated by solving the Fick's diffusion equation. Finally, we successfully fabricate a GI tapered core polymer waveguide as designed.

10109-6, Session 2

Design of signal router employing optical switching in MIM plasmonic waveguides

Lokendra Singh, Amna Bedi, Santosh Kumar, DIT Univ. (India)

The all optical routing is novel approach for establishment of transparent information flow in optical networks. The diffraction limit of light is major factor which backseats the photonic components and mitigated by integrated all optical components. In this paper, an all optical signal router with two optical inputs using nonlinear plasmonic Mach-Zehnder interferometer (MZI) is proposed. The nonlinearity in MZI structure is achieved by using nonlinear Kerr material, which is also responsible for switching of optical signal across two output ports. The study of proposed device is carried out using finite difference time domain (FDTD) method and verified using MATLAB.

10109-7, Session 2

Understanding the source of dielectric loss in Titania/polypropylene nanocomposites up to 220 GHz

Michael D. Womble, Julia W. P. Hsu, Yun-Ju Lee, The Univ. of Texas at Dallas (United States); Juan A. Herbsommer, Texas Instruments, Inc. (United States)

As the speed of data communications approaches the sub-THz regime, the material choice for interconnects becomes a challenging problem. Metals which are used at lower frequencies are too lossy at these high frequencies due to the skin effect. Wireless communication is also difficult for compact devices due to the r2 decay in radiated waves, and the small aperture size of sub-THz (typically ?/2) receiving antennas limits the absorption cross section for incoming radiation. Low loss polymers have demonstrated the potential to guide THz waves over long distances; however, the low refractive index of polymers limits the density of interconnects. Polymer nanocomposites, which consist of inorganic nanoparticles in a polymer matrix, can take advantage of the low loss of the polymer and the high dielectric constant of the filler. The higher dielectric constant of these polymer nanocomposites allow for a reduction in waveguide dimensions. In this study rutile $TiO2$ and Si nanoparticles were shear-mixed into a polypropylene (PP) matrix using a compatibilizer, polypropylene-graft-Maleic anhydride (PP-g-MA). These nanocomposites demonstrate 2 to 3-fold enhancement in the dielectric constant over that of pure PP at frequencies between 140 and 220 GHz. However, the loss of the Si nanocomposites was significantly higher than that of $TiO2$ nanocomposites at these high frequencies. Future studies will focus on understanding the origin of and the strategies to decrease the loss, and the effect of filler shape on the dielectric constant of these composites.

10109-8, Session 2

Plasmonic modulators and switches *(Invited Paper)*

Juerg Leuthold, Alexandros Emboras, Claudia B. Hoessbacher, Wolfgang Heni, Christian Haffner, Ueli Koch, Yannick Salamin, Yuriy M. Fedoryshyn, ETH Zürich (Switzerland)

A rich variety of plasmonic modulators and switches is emerging. They offer ultra-compact size in the order of a few micrometers, bandwidths from the MHz to the THz, low power consumption and they operate across a large spectral range. Some plasmonic devices are latching and others offer linear performance. Plasmonic devices not only come in a variety of shapes but also rely on various physical phenomena such as the thermal effect, the free carrier dispersion effect, the Pockels effect, the material phase change effect or they may rely on electrochemical metallization effects. After a discussion on the physics of plasmonics we will conclude the talk with a discussion of the opportunities and challenges related to plasmonics in optical communications and in particular with respect to applications in optical interconnects.

10109-9, Session 2

Hybrid photonics: combining organic and inorganic semiconductors in visible light communications *(Invited Paper)*

Ifor D. W. Samuel, Univ. of St. Andrews (United Kingdom)

Visible light communication (VLC) is an emerging field, also known as "Li-Fi" in which room lighting is used for data communication. Solid state lighting is modulated to encode information and a receiver is placed on connected devices such as computers, printers, and smartphones. Organic semiconductors are semiconductors based on conjugated organic materials and typically combine novel semiconducting optoelectronic properties, with simple fabrication and the scope to tune properties by changing their chemical structure. Of particular relevance to VLC is the fact that organic semiconductors combine strong absorption, high fluorescence quantum yield and short radiative lifetime. This makes them attractive materials for colour conversion. Inorganic LED light fittings consist of a blue gallium nitride LED together with an inorganic phosphor. The latter has a long excited state lifetime that severely limits the bandwidth of data transmission. The short radiative lifetime of conjugated polymers makes them attractive materials to overcome this limitation. The copolymer super-yellow was used in combination with a gallium nitride micro-LED to generate white light. This enabled data transmission at 1.68 Gb/s over a distance of 3 cm, and 840 Mb/s over a distance of 2 m. These results are the fastest so far reported for a visible light communication system with a single white-source. Another challenge in VLC is to detect the signal with high signal to noise and high bandwidth. Increasing the area of a detector typically increases its sensitivity but also increases its response time, thereby reducing its bandwidth. It will be shown how fluorescent organic materials can be used to overcome this limitation.

10109-10, Session 3

CWDM transceiver for mid-board optics *(Invited Paper)*

Paul Rosenberg, Mike Tan, Hewlett-Packard Co. (United States); Sagi Mathai, Wayne V. Sorin, Hewlett-Packard Labs. (United States); George Panotopoulos, oeWorks Inc. (United States); Kent Devenport, Hewlett-Packard Co. (United States); Darrell Childers, D. J. Hastings, US Conec Ltd. (United States); Glenn Rankin, George Megason, David Moore, Gregg Combs, Hewlett Packard Enterprise (United States)

The need for additional IO bandwidth for data center device interconnection is well established. Optical interconnects can deliver this bandwidth along with energy and space efficiency at a cost that encourages adoption.

To this end, we are developing an optical transceiver incorporating multimode VCSEL emitters in a coarse wavelength division multiplexed (CWDM) system capable of transmission at 25Gbps per channel and an aggregate bidirectional data rate of 1.2Tbps. Electrical connection to the transceiver can be made by solder reflow or LGA connector, and optical connection is made by means of a custom optical connector supporting CWDM transmission.

10109-11, Session 3

A Mechanical-Optical Interface for 25+ Gbps VCSEL/PD Fiber Coupling

Dirk Schoellner, Sharon M. Lutz, Ke Wang, Dan Kurtz, US Conec Ltd. (United States); Terrence Kerr, Mike Wang, O-NET Communications (USA) Inc (United States)

As parallel optics data rates transition from 10 Gbps to 25 Gbps and beyond, VCSELs and PDs are evolving to support higher transmission rates. In order to maintain system performance as speeds increase and tolerances become tighter, an improved method is needed to efficiently couple VCSEL/ PD arrays to fiber optic networks.

A mechanical-optical interface (MOI), designed for efficient coupling between on-board active components and a detachable fiber optic connector, is a monolithic injection molded polymer component with an array of collimating lenses.

This paper describes the design of the next generation MOI to support high speed VCSEL/PD requirements. The new mechanical design was improved to accept a wider variety of transceiver architectures, taking into account the chip driver and wire-bond clearance requirements, while also optimizing the optical design to maximize coupling performance. A broad range of VCSEL/ PD parameters are examined with Monte Carlo simulations and sensitivity analysis to optimize optical performance with respect to alignment requirements.

Empirical testing will be presented to validate the optical model and subsequent system performance. System metrics will include characterizations such as bit-error-rate testing, eye diagram results, and link loss measurements. Environmental and mechanical testing of the component after alignment and adhesion to the circuit substrate will validate part performance.

10109-12, Session 3

WDM mid-board optics for chip-to-chip wavelength routing interconnects in the H2020 ICT-STREAMS *(Invited Paper)*

George T. Kanellos, Nikos Pleros, Aristotle Univ. of Thessaloniki (Greece)

Multi-socket server boards have emerged to increase the processing power density on the board level and further flatten the data center networks beyond leaf-spine architectures. Scaling however the number of processors per board puts current electronic technologies into challenge, as it requires high bandwidth interconnects and high throughput switches with increased number of ports that are currently unavailable. On-board optical interconnection has proved the potential to efficiently satisfy the bandwidth needs, but their use has been limited to parallel links without performing any smart routing functionality. With CWDM optical interconnects already a commodity, cyclical wavelength routing proposed to fit the datacom for rack-to-rack and board-to-board communication now becomes a promising on-board routing platform.

ICT-STREAMS is a European research project that aims to combine WDM parallel on-board transceivers with a cyclical AWGR, in order to create a new board-level, chip-to-chip interconnection paradigm that will leverage WDM parallel transmission to a powerful wavelength routing platform capable to interconnect multiple processors with unprecedented bandwidth and throughput capacity. Direct, any-to-any, on-board interconnection of multiple processors will significantly contribute to further flatten the data centers and facilitate east-west communication. In the present communication, we present ICT-STREAMS on-board wavelength routing architecture for multiple chip-to-chip interconnections and evaluate the overall system performance in terms of throughput and latency for several SDN schemes and traffic profiles. We also review recent advances of the ICT-STREAMS platform key-enabling technologies that span from Si in-plane lasers and polymer based electro-optical circuit boards to silicon photonics transceivers and photonic-crystal amplifiers.

10109-13, Session 3

VCSEL-based optical transceiver module for high-speed short-reach interconnects *(Invited Paper)*

Takatoshi Yagisawa, Hideki Oku, Tatsuhiro Mori, Rie Tsudome, Kazuhiro Tanaka, Osamu Daikuhara, Takeshi Komiyama, Satoshi Ide, Fujitsu Component Ltd. (Japan)

Optical transceivers are widely used for high-performance computing systems and high-end servers as active optical cables (AOCs) or on-board optical modules instead of conventional copper cables. Requirements for optical interconnects are that they be high-speed, have a longer transmission distance, be highly reliable and so on. However, the most pressing requirement that they be low cost. To satisfy these requirements,

we proposed a vertical-cavity surface-emitting laser (VCSEL) based cost-effective optical engine. The optical engine consists of a flexible printed circuit (FPC) on which a VCSEL array, driver integrated circuit (IC), photodiode (PD) array, and transimpedance amplifier (TIA) are mounted by flip-chip bonding. A thin microlens-imprinted film pasted on a polymer waveguide having 45-degree mirrors is attached to the bottom of the FPC. The structure of the optical engine is designed such that can be assembled with passive alignment assembly processes for all of the components by standard flip-chip bonder to reduce the cost of manufacturing.

In this paper, techniques that enable to assemble the optical engine with passive alignment processes and the actual results that show the relationship between the position tolerance of the optical devices and optical coupling losses will be discussed. The high-speed electrical and optical performances up to 40 Gbps of our optical engines and transceiver modules will be also discussed.

10109-14, Session 3

PAM4 silicon photonic microring resonator-based transceiver circuits *(Invited Paper)*

Samuel Palermo, Kunzhi Yu, Ashkan Roshan-Zamir, Binhao Wang, Texas A&M Univ. (United States); Cheng Li, M. Ashkan Seyedi, Marco Fiorentino, Raymond G. Beausoleil, Hewlett Packard Enterprise (United States)

Increased data rates have motivated the investigation of advanced modulation schemes, such as four-level pulse-amplitude modulation (PAM4), in optical interconnect systems in order to enable longer transmission distances and operation with reduced circuit bandwidth relative to non-return-to-zero (NRZ) modulation. Employing this modulation scheme in interconnect architectures based on high-Q silicon photonic microring resonator devices, which occupy small area and allow for inherent wavelength-division multiplexing (WDM), offers a promising solution to address the dramatic increase in datacenter I/O bandwidth demands. Two ring modulator device structures are proposed for PAM4 modulation, including a single-segment device driven with a multi-level PAM4 transmitter and a two-segment device driven by two simple NRZ (MSB/LSB) transmitters. A silicon photonic microring resonator modulator transmitter which utilizes a segmented pulsed-cascode output stage for voltage level control to achieve PAM4 modulation on a single microring device is presented. Implemented in 65nm CMOS, the transmitter achieves 40Gb/s operation at 3.04mW/Gb/s when driving depletion-mode microring modulators with 4.4Vppd swing. A PAM4 optical receiver front-end is also described which employs a large input-stage feedback resistor transimpedance amplifier (TIA) cascaded with an adaptively-tuned continuous-time linear equalizer (CTLE) for improved sensitivity. Receiver linearity, critical in PAM4 systems, is achieved with a peak-detector-based automatic gain control (AGC) loop.

10109-15, Session 3

Silicon photonic transceivers for beyond 1-Tb/s datacom applications *(Invited Paper)*

Segolene Olivier, Corrado Sciancalepore, Karim Hassan, Daivid Fowler, Badhise Ben Bakir, CEA-LETI (France); Thomas Ferroti, CEA-LETI (France) and STmicroelectronics (France); Hélène Duprez, CEA-LETI (France); Jocelyn Durel, STMicroelectronics N.V. (France) and CEA-LETI (France); Alexis Abraham, Simon Plantier, Bertrand Szelag, Sylvie Menezo, CEA-LETI (France); Charles Baudot, Frédéric Boeuf, STMicroelectronics (France); Frederic Y. Gardes, Nannicha Hattasan, Univ. of Southampton (United Kingdom); Liam O'Faolain, Univ. of St. Andrews (United Kingdom); Delphine Marris-Morini, Institut d'Électronique Fondamentale, Univ. Paris-Sud (France); Andrea Ghilioni, Univ. degli Studi di Pavia (Italy); Melchiorre Bruccoleri, STMicroelectronics N.V. (Italy); Anthony Martinez, Finisar Germany GmbH (Germany); Richard C. Pitwon, Seagate Systems (UK) Ltd. (United Kingdom); Nino Crameri, Tobias Lamprecht, vario-optics ag (Switzerland)

The field of silicon photonics is attracting a lot of attention due to the prospect of low-cost and compact circuits that integrate photonic and microelectronic elements on a single chip. Such silicon chips have applications in optical transmitter and receiver circuits for short-distance communications as well as for long-haul optical transmissions. Silicon photonics has proven to be a successful platform for many functional elements such as low-loss waveguides, filters, multiplexers/demultiplexers, optical modulators and Ge-on-Si photodiodes. On-going developments for advanced photonic integrated circuits include compact and energy-efficient silicon modulators, temperature-insensitive passive devices and hybrid III-V on Silicon lasers.

The European COSMICC project gathers key industrial and research partners in the field of silicon photonics, CMOS electronics, printed circuit board packaging, optical transceivers and datacenters, aiming at developing low-cost and low-energy consumption 50 Gb/s 4-wavelength coarse wavelength division multiplexing optical transceivers that will be packaged on-board. Combining CMOS electronics and Si-photonics with innovative high-throughput fiber attachment techniques, the developed solutions will be scalable beyond 1 Tb/s to meet the future data-transmission requirements in data-centers and super computing systems.

10109-16, Session 4

Pluggable multimode edge connector for glass-based electro-optical circuit boards (EOCB)

Lars Brusberg, Randy L. McClure, Davide D. Fortusini, Douglas L. Butler, Qi Wu, Christopher P. Lewallen, Jerald L. Overcash, Corning Incorporated (United States)

Glass waveguides fabricated by ion-exchange are a promising technology for short reach on-board optical interconnects because of their low loss (<0.1 dB/cm) at 1310nm. The waveguides are integrated in a glass sheet and their end faces can be laser-processed to have good optical quality. Embedding in printed circuit boards has been previously studied, and multiple demonstrations showed the feasibility of fabricating electro-optical circuit boards (EOCB) with optical layers made of glass.

For off-board interconnects, the optical fiber connector is a necessary component; it should be pluggable, low-loss, reliable, and cost-effective. We developed an optical connector concept for the interconnection of EOCBs to multimode fiber ribbon cables. Our concept is based on the MXC® expanded-beam connector. A modified version of the US Conec PRIZM® MT ferrule is installed on the edge of the glass waveguide panel by adhesive bonding. The lens array of the modified PRIZM® MT ferrule collimates the beam emitted by the glass waveguides, and it allows mating to a fiber ribbon cable having an MXC® connector. We developed the assembly process to align the modified PRIZM® MT ferrules in front of the waveguide array, and installed connectors on both ends of an array of 17-cm-long waveguides. To assess the connector loss, we measured the optical loss before and after installation of the connectors: we found that the loss introduced by each expanded-beam connector is less than 1 dB. The paper will discuss the connector concept, the assembly process, the demonstrator platform and the characterization results.

10109-17, Session 4

Accurate core position control in polymer optical waveguides using the Mosquito method for three-dimensional optical wiring

Kumi Date, Takaaki Ishigure, Keio Univ. (Japan)

Polymer optical waveguides with graded-index (GI) circular cores are fabricated using the Mosquito method, in which the positions of parallel cores are accurately controlled. Such an accurate arrangement is of great importance for a high optical coupling efficiency with other optical components such as fiber ribbons. In the Mosquito method that we developed, a core monomer with a viscous liquid state is dispensed into another liquid state monomer for cladding via a syringe needle. Hence, the core positions are likely to shift during or after the dispensing process due to several factors. We investigate the factors, specifically affecting the core height. When appropriate core and cladding monomers are selected, the effect of the gravity could be negligible, so the core height is maintained uniform, resulting in accurate core heights. The height variance is controlled in ±2 micrometers for the 12 cores.

Meanwhile, larger shift in the core height is observed when the needle-tip position is apart from the substrate surface. One of the possible reasons of the needle-tip height dependence is the asymmetric volume contraction during the monomer curing. We find a linear relationship between the original needle-tip height and the core-height shift. This relationship is implemented in the needle-scan program to stabilize the core height in different layers. Finally, the core heights are accurately controlled even if the cores are aligned on various heights. These results indicate that the Mosquito method enables to fabricate waveguides in which the cores are 3-dimensionally aligned with high position accuracy.

10109-18, Session 4

Insertion loss study for panel-level single-mode glass waveguides

Marcel Neitz, Technische Univ. Berlin (Germany); Julia Röder-Ali, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Sebastian Marx, Technische Univ. Berlin (Germany); Christopher Frey, Christian Herbst, Henning Schröder, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Klaus-Dieter Lang, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany) and Technische Univ. Berlin (Germany)

Following the large bandwidth demand in long range communication, integration of single-mode waveguides into medium and short range equipment is ongoing in order to provide high data rate to cover the demands. According to these shifts in communication technology, an intra-board as well as an inter-board communication by single-mode waveguides is necessary. To decrease manufacturing costs and increase the amount of fabricated boards, panel-level processing of optical waveguides was developed over the last years for multiple optical media like polymer, silicon or glass waveguides. Due to low propagation losses, glass is a good choice for 18"x24" panels or even larger boards. The paper presents some project results, e.g. of the ongoing PhoxTroT EU-project where we processed single-mode structures at panel- and wafer-level with losses as low as 0.1 dB/cm. The paper compares the results of panel- and wafer-level processing. The comparison is based on measurements of the same optical structures on panel- and on wafer-level. Additionally, larger panels of 440 mm x 305 mm where also manufactured to prove the scalability of the single-mode process onto large panels. Measurements are done by optical back scattering reflectometry using an OBR 4600 and a fiber-based propagation loss measurement setup. Based on these results of diverse processing equipment and substrate dimensions, a comprehensive statistic is shown and error estimation made to compare the different technologies.

10109-19, Session 4

Single-mode polymer waveguide PCBs for on-board chip-to-chip interconnects

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Pluggable optics are being pushed to their limits in terms of face plate density and power consumption requirements within emerging mega data centers and HPCs applications. Future applications seek silicon photonics based optical engines with ability for high channel count and throughput beyond 1Tb/s. In this paper, we show our results in development of single mode polymer-based optical-electrical PCBs (OEPCBs) supporting the emerging Si-Pho host PCB platforms with multi-terabit on-board routing capability for chip-to-chip communications. Single mode polymer waveguides (SM-PWGs) are fabricated using new photopatternable optical silicone materials (WG-2211/WG-2511-WG2711) on conventional PCBs. Test platform PCB shows designs with varying core sizes (20/15/12/9/7μm) and channel lengths (5-15cm). The measurements results show single-mode waveguides loss as less 0.4 dB/cm at 1310nm. Furthermore, the result show new waveguide material to be compliance for both rigid and flexible PCBs. OEPCB compliance evaluation test results shown in the paper includes results of lamination, chemical compliance, drilling, and plating tests. The results shown in the paper show first time ever fabrication of single mode polymer waveguide OEPCBs in production environment.

10109-20, Session 5

Low-dimensional photonic crystal waveguide modulators for 100-Gbs applications *(Invited Paper)*

Bruce W. Wessels, Northwestern Univ. (United States)

Optical communication networks – long-haul and short-reach as well as classical and quantum-based networks of the future – require modulators that actively alter the phase, amplitude, wavelength, and polarization of light. For decades, lithium niobate electro-optic (EO) modulators have met the requirements for EO modulation in long-haul networks. However, as optical links continue to present ever-greater advantages at shorter length scales, other more compact and integrable material platforms have been investigated, including silicon, indium phosphide, and, most recently, two-dimensional materials. Although much progress has been made on Si and InP and there is much promise for 2D materials, no technology to date has been shown with the concomitant properties of high EO bandwidth, wide optical range, low voltage, and compact size. To address this need, we have taken the approach of developing thin film $BaTiO_3$ as an optoelectronic platform for high frequency, low voltage, and compact modulators. Epitaxial $BaTiO_3$ films are a silicon-compatible optoelectronic material with among the highest known EO coefficient, more than 10 times larger than that of $LiNbO_3$. Using $BaTiO_3$ thin films with 1 mm long interaction length, we have previously demonstrated intensity modulators with voltage-length products nearly an order of magnitude smaller than that of silicon. We have also shown the potential for high frequency operation by demonstrating modulation out to 50 GHz and 28 GHz 3 dB EO bandwidth. Here we demonstrate the high-frequency and low-voltage phase modulation of light using epitaxial thin film $BaTiO_3$. Clear EO phase modulation of 1550 nm light is measured out to 50 GHz using an optical spectral analysis method. We also show that, by incorporating low dimensional, photonic crystal (PC) waveguides to enhance the EO coefficient, the operating voltage can be significantly reduced.

10109-21, Session 5

VCSEL design and integration for high-capacity optical interconnects *(Invited Paper)*

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By optimized active region and cavity designs, the modulation bandwidth of 850 nm VCSELs has been extended to 30 GHz while energy dissipation has been reduced to <100 fJ/bit at 25-50 Gbit/s. Transmission under OOK modulation at data rates up to 71 and 57 Gbit/s has been demonstrated with and without equalization, respectively. More advanced modulation formats offer even higher capacities. PAM-4 together with pre-emphasis, equalization and forward error correction has enabled near 100 Gbit/s transmission.

The spatial domain has been explored for further capacity improvements by the development of arrays of high-speed VCSELs for multicore fiber interconnects. A single fiber aggregate capacity of 240 Gbit/s has been demonstrated.

The wavelength domain is explored by the development of techniques for multi-wavelength VCSEL arrays and wavelength multiplexing. This includes methods for wavelength setting in a post-epitaxial growth process and VCSEL integration on silicon photonic platforms for multiplexing.

10109-22, Session 5

Silicon high-speed lumped modulator and other energy-saving approaches for optical interconnects *(Invited Paper)*

Zhiping Zhou, Xinbai Li, Qingzhong Deng, Peking Univ. (China)

As optical communication and interconnection capacity rapidly move beyond 100G, energy consumption per bit becomes one of the vitally important aspects of device requirement if the development is to be sustainable. In this talk, we will present our latest research on devices for low energy consumption optical interconnects. Conventional traveling-wave silicon modulators consume considerable energy, while lumped silicon modulators can be energy efficient but their speed has been limited to 10 Gbaud, insufficient for current 28Gbaud requirement. We propose the complete analytical electro-optic theory of lumped silicon modulators. Comprehensive analysis empowered by the theory reveals the speed limitation and single-drive configuration is introduced to substantially improve modulation speed. It is also shown that more than an order of magnitude energy reduction compared with traveling wave modulators is achievable, making lumped modulators a promising substitute at 28 Gbaud rate. When driven by low impedance driver, modulation energy can be as low as ~20 fJ/bit, marking a huge step toward 10 fJ/bit energy goal. Secondly, traditional interleaved junctions were reported to cause higher energy consumption due to considerable junction capacitance, despite the enhancement of modulation efficiency. We propose novel interleaved PN junction to improve light-carrier overlap and resolve the efficiency-energy conflict. Finally, athermal flat-top silicon Mach-Zehnder multiplexer and demultiplexer can eliminate the need for thermal control and thus achieve an energy-free multiplexing for WDM systems. These energy saving methods are instructive in future optical communication systems.

10109-23, Session 5

One-dimensional photonic crystal slot waveguide for silicon-organic hybrid electro-optic modulators

Hai Yan, The Univ. of Texas at Austin (United States); Xiaochuan Xu, Omega Optics, Inc. (United States); Chi-Jui Chung, The Univ. of Texas at Austin (United States); Harish Subbaraman, Omega Optics, Inc. (United States); Zeyu Pan, The Univ. of Texas at Austin (United States); Swapnajit Chakravarty, Omega Optics, Inc. (United States); Ray T. Chen, The Univ. of Texas at Austin (United States) and Omega Optics, Inc. (United States)

Silicon-organic hybrid electro-optic (EO) modulator is a promising solution for on-chip integrated modulator applications. This type of EO modulators combines the benefits of both silicon photonics and organic materials, enabling high-frequency, high-efficiency operation. Various phase shifter designs for silicon-organic hybrid modulators have been reported, including strip-loaded slot waveguide and two-dimensional slot photonic crystal (PC) waveguide. Here, we propose and experimentally demonstrate a novel one-dimensional (1D) photonic crystal (PC) slot waveguide for integrated silicon-organic hybrid modulators. The 1D PC slot waveguide consists of a conventional silicon slot waveguide with periodic rectangular teeth on its rails. This structure takes advantage of large mode overlap in a conventional slot waveguide and the slow light enhancement from the PC structure. Its simple geometry also helps reduce the propagation loss and improve robustness to fabrication imperfections. Using 200 ?m of the proposed 1D PC slot waveguide as a phase shifter in a Mach-Zehnder interferometer, an integrated silicon-organic hybrid EO modulator was experimentally demonstrated. To compensate the mode mismatch at the interface of 1D PC slot and regular slot waveguide, a short step index taper (~2 ?m) is introduced. The observed effective EO coefficient in the modulator is as high as 490 pm/V. The measured half-wave voltage and length product is less than 1V·cm and can be further improved. The total on-chip loss is only about 10 dB. The proposed structure offers a competitive novel phase shifter design that is simple, highly efficient and with low optical loss, for on-chip silicon-organic hybrid EO modulators.

10109-24, Session 5

Broadband hybrid electro-optic polymer device to silicon Mach-Zehnder modulator

Shiyoshi Yokoyama, HIroki Miura, Hiromu Sato, Feng Qiu, Kyushu Univ. (Japan)

We demonstrate the hybrid silicon and electro-optic (EO) polymer modulator for low-driving voltage and high bandwidth applications. The designed hybrid waveguide was fabricated by the conventional photolithography technique, so that this widespread compatibility enabled the construction of the unique polymer photonic devices. The waveguide consists of the silicon core with a 50 nm-thick and 2 ?m-wide core and the EO polymer cladding. The optical mode calculation indicates that the large extension of the optical field into the EO polymer provides the EO coefficient of about 80 pm/V in the waveguide. Therefore, the half-wave voltage of the hybrid waveguide was recorded only 1.1 V at 1550 nm in the Mach-Zehnder modulator. The measured insertion loss was about 15 dB, which included the materials absorption loss of the EO polymer. The traveling-wave-electrodes were applied to the hybrid waveguide in order to evaluate the frequency response of the modulator up to 40 GHz by measuring the S21 parameter. The -3 dB bandwidth of 20 GHz and a 6 dB reduction in response at 40 GHz were measured. This bandwidth is mainly limited by the conductor loss of the electrode, which can be improved further by the fabrication. The hybrid waveguide showed the excellent temperature stability at 85C for longer than 2000 hours.

10109-25, Session 6

Measurement of mid-IR transmission in semiconductor core fibers

Mustafa Ordu, Jicheng Guo, Boyin Tai, Shyamsunder Erramilli, Siddharth Ramachandran, Soumendra N. Basu, Boston Univ. (United States)

Mid-infrared (IR) fibers have been extensively investigated due to their applicability in chemical sensing and remote laser delivery, among others. Materials such as chalcogenides and fluoride glasses transmit mid-IR wavelengths with low practical losses. However, their low glass transition temperatures make them chemically unstable, even at room temperatures, resulting in performance degradation over time. Semiconductors, such as germanium, have a wide transmission window in the mid-IR region, and offer significantly improved chemical stability. In this research, germanium-core, borosilicate-cladded fibers were drawn by a 'rod in tube' method using a mini draw tower assembled in-house at 1000°C, which is significantly lower than the drawing temperatures of 2000-2200°C for conventional silica fibers. Typical drawn fibers had a 40 ?m core diameter and 177 ?m cladding diameter. Transmission electron microscopy (TEM) studies showed that diffusion of oxygen and silicon from the cladding to the core during the drawing process was minimal, with diffusion distances of the order of 10s of nm. This is encouraging for mid-IR transmission, since the presence of oxygen in the fiber core is known to increase transmission losses in the mid-IR spectrum. This low diffusivity is presumably due to the relatively low drawing temperature. Transmission losses through the fibers were measured with a quantum cascade laser (QCL) and the losses were found to be in the 3-9 dB/cm range in the spectral range of 5.75-6.3 ?m.

10109-26, Session 6

Fiber bundle probes for interconnecting miniaturized medical imaging devices

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Miniaturization of medical imaging devices will significantly improve the workflow of physicians in hospitals. Photonic integrated circuitry (PIC) technologies offer a high level of miniaturization. However, they need fiber interconnection solutions for their functional integration. We investigate fiber bundle probes (FBPs) to be used as multi-mode (MM) to single-mode (SM) interconnections for PIC modules. The FBP consists of a set of seven SM fibers hexagonally distributed and assembled into a silica or metal capillary which can operate as a MM end port. Simulations are performed via functional mode solver tools in order to study the performance as a function of structural parameters such as core size and core spacing at wavelengths of 635 nm and 1550 nm. The manufacturing of these probes requires stable and well-controlled fiber fusion, etching and adhesive technologies in order to achieve low-loss and reproducible samples. An innovative fiber etching technology based on molten salts has been investigated. The preliminary results show that the reduction of the fiber diameter shows a linear behavior as a function of etching time. Different etch rate values from 0.55 μm/min to 2.3 μm/min were found. Two types of probes operating at 1550 nm were successfully developed with seven SM fibers of 80 μm diameter and etched fibers up to 65 μm. FBPs present moderate optical losses and they might be also integrated using different fibers, covering a broad spectral range required for imaging applications. Finally, we show the use of FBPs as promising MM-to-SM interconnects for real-world interfacing to PIC's.

10109-27, Session 6

Multimode Fiber for High-Density Optical Interconnects *(Invited Paper)*

Scott R. Bickham, Radawan Ripumaree, Julia A Chalk, Mark T Paap, William C Hurley, Corning Optical Communications (United States); Randy L McClure, Network Integration and Connectivity Research (United States)

Data centers (DCs) are facing the challenge of delivering more capacity over longer distances, and a great deal of attention is being given to the trade-offs between multimode and single-mode fibers, particularly in hyper-scale DCs. These fibers are currently used in conjunction with pluggable modules and AOC's on the card edge. However as line rates increase to 25 Gb/s and higher, DCs are being challenged with signal integrity issues due to the long electrical traces that require re-timing. In addition, the density of interconnects on the front panel is limited by the size and power dissipation requirements of the pluggable modules. One proposal to overcome these issues is to use embedded optical transceivers in which optical fibers are used to transport data to and from the front panel. These embedded modules will utilize arrays of VCSEL or silicon-photonic transceivers, and in both cases, the capacity will be limited by the density of the optical connections on the chip. To address this constraint, we have designed an optical fiber in which the coating diameter is reduced from 250 to 125 microns without compromising low-loss connectivity. This smaller diameter fiber enables twice as many optical interconnects in the same footprint, and this in turn will allow the transceiver arrays to be collinearly located on small chips with dimensions on the order of 5mmx5mm. We have also incorporated these reduced diameter fibers into small, flexible 8-fiber ribbon cables which simplify routing constraints inside the modules.

10109-28, Session 6

Micro/nanoscale self-aligned optical couplings of the self-organized lightwave network (SOLNET) formed by two-photon photochemistry

Tetsuzo Yoshimura, Tokyo Univ. of Technology (Japan)

One of the technical issues in the optical interconnects is the coupling between optical devices. To solve these problems, we previously proposed a coupling method based on the self-organized lightwave network (SOLNET) formed by self-focusing in photo-induced refractive-index increase (PRI) materials such as photopolymers. SOLNETs are formed by an attractive force between light beams in the PRI material to form self-aligned coupling waveguides between optical devices, even if misalignments and core size mismatching exist, operating as an optical solder.

In the present work, in order to extend the lateral misalignment tolerance between nanoscale waveguides and between microscale and nanoscale waveguides, we propose the two-photon SOLNET, which is formed using two-photon photochemistry. Simulations based on the finite-difference time-domain method reveal that the two-photon SOLNETs increase the tolerance up to 4200 nm from 600 nm, which is available in the one-photon SOLNETs, for couplings between 600-nm-wide waveguides facing each other with 32-?m gap. For couplings between 3000-nm-wide and 600-nm-wide waveguides, the tolerance increases to 3000 nm from 600 nm by intraducing the two-photon photochemistry.

Preliminary experiments demonstrate that the two-photon SOLNETs are formed between multimode optical fibers by introducing a 448-nm write beam and a 780-nm (or 856-nm) write beam from the fibers into a photosensitive organic/inorganic hybrid material, SUNCONNECT®, with doped camphorquinon (or biacetyl).

10109-29, Session 7

A scalable silicon photonic switch platform with integrated gain using flip-chip SOA arrays *(Invited Paper)*

Fuad E. Doany, IBM Thomas J. Watson Research Ctr. (United States)

Optical switch networks based on silicon photonics can provide high bandwidth, low latency, low power, and low cost interconnect fabrics for datacenter, cloud, and high-performance computing by eliminating the pin-constrained electronic switches and the multiple electrical-optical conversions necessary in traditional networks. Silicon photonics is also compatible with wavelength division multiplexing (WDM) allowing simultaneous routing of large bandwidth data streams. Adoption of photonic switches requires scaling to large port counts compared to current 4x4 and 8x8 demonstrations. For example, a 64-port switch implemented using thirty-two 4x4 and four 16x16 switches will be limited by losses in numerous subcomponents, including optical couplers, waveguide propagation losses, waveguide crossings, and phase shifters. To enable viable optical-link-loss budgets requires incorporation of optical gain in addition to improved efficiency in all subcomponents.

We have developed a silicon photonic switch platform with integrated gain based on a carrier with active photonics. Optical switches are monolithically integrated into photonic carrier while semiconductor optical amplifiers (SOAs) and CMOS drive ICs are flip-chip attached. We demonstrated non-blocking 4x4 Si photonic switches with < 3-dB on-chip loss and < -20 dB crosstalk with about 4ns switching time. Photonic carriers and 4-channel SOA arrays were co-designed with custom precision packaging features enabling flip-chip bonding with high accuracy. The photonic carrier incorporates low-loss SiN waveguides with inverse taper structures for efficient coupling to/from the SOA arrays and off-carrier coupling. Photonic carriers with integrated 4-channel SOA arrays were fabricated achieving over 10 dB gain and demonstrating error-free 4x25-Gb/s WDM links for all 4 channels.

10109-30, Session 7

Optical CAM architecture for address look-up at 10 Gb/s

Pavlos Maniotis, Aristotle Univ. of Thessaloniki (Greece); Nikos Terzenidis, Aristotle University of Thessaloniki (Greece); Nikos Pleros, Aristotle Univ. of Thessaloniki (Greece)

Content Addressable Memories (CAMs) are widely used in nowadays router applications due to their fast bit searching capabilities. However, address loop-up operation cannot still keep up with high data-rate speeds of optical packet payload due to the limited speeds offered by electronics, which hardly can reach a few GHz. Despite this limitation, optics has still not managed to penetrate in the area of look-up and forwarding operations due to the complete lack of optical CAM-based solutions. The first all-optical binary CAM-cell has been only recently experimentally demonstrated by our group using an all-optical monolithically integrated InP Flip-Flop and an optical XOR gate, revealing error-free operation at 10 Gb/s for both Content Addressing and Content Writing operations. In this paper, we extend our previous work by presenting for the first time to our knowledge an all-optical Ternary CAM-cell architecture that allows also for a third matching state of “X” or “don’t care”, thus adding the necessary searching flexibility required by modern CAM-based solutions for supporting subnet-masked addresses. Moreover, we exploit the optical Ternary CAM cell towards deploying a complete CAM-row formed by 4 Ternary CAM cells, demonstrating its operation through VPI simulations at 10Gb/s for an indicative 4-bit packet address and for both Content Addressing and Content Writing functionalities. The potential of this memory architecture to allow for up to 40Gb/s operation could presumably lead to fast CAM-based routing applications by enabling all-optical Address Look-up schemes.

10109-31, Session 7

Modeling, simulation, and measurement of a bidirectional optical interconnection system for industrial applications

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This paper presents a bidirectional optical data transmission system as an enhancement of a contactless power transmission system (CPTS). The latter consists of two separate devices and is able to transmit up to 240W electrical power using inductive resonant coupling. The optical system consists of two self-developed light-guiding structures and a short-reach free-space optical path. As source and sink of the latter a light-emitting diode resp. a photodiode with a centroid wavelength of 850nm are used. The optical system is positioned within the CPTS; it transmits the PROFIBUS protocol to fulfill industry 4.0 needs.

Due to the restrictions given by the applications areas of the CPTS, such as air gap up to 5mm, misalignment up to 2mm, tilting up to 5° and rotation angle up to 360°, different kinds of light-guiding structures were analyzed by simulation. Based on these results the promising structures are selected and manufactured. Hereafter the attenuation and the near field characteristic of one light-guiding structure is analyzed. After this, the attenuation based on misalignment, variation of air gap, tilting and rotation between two light-guiding structures are analyzed by measurement. To check whether the requirements of the PROFIBUS has been satisfied by the complete data transmission system, the transient transmission behavior of the latter was analyzed by a pseudo-random bit stream.

In the paper the most important results of the design, the simulation and the measurement are explained. The presented results demonstrate the ability to design of such systems based on simulations and to evaluate the suitability of various geometries for present and future works.

10109-32, Session 7

A programmable Si-photonic node for SDN-enabled Bloom filter forwarding in disaggregated data centers

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Programmable switching nodes supporting Software-Defined Networking (SDN) over optical interconnects arise as a key enabling technology for future disaggregated Data Center (DC) environments. The SDN-enabling roadmap of intra-DC optical solutions is already a reality for rack-to-rack interconnects, with recent research reporting on interesting applications of programmable silicon photonic switching fabrics addressing board-to-board and even on-board applications. In this perspective, simplified information addressing schemes like Bloom filter (BF)-based labels emerge as a highly promising solution for ensuring rapid switch reconfiguration, following quickly the changes enforced in network size, network topology

or even in content location. The benefits of BF-based forwarding have been so far successfully demonstrated in the Information-Centric Network (ICN) paradigm, while theoretical studies have also revealed the energy consumption and speed advantages when applied in DCs. In this paper we present for the first time a programmable 4x4 Silicon Photonic switch that supports SDN through the use of BF-labeled router ports. Our scheme significantly simplifies packet forwarding as it negates the need for large forwarding tables, allowing for its remote control through modifications in the assigned BF labels. We demonstrate 1x4 switch operation controlling the Si-Pho switch by a Stratix V FPGA module, which is responsible for processing the packet ID and correlating its destination with the appropriate BF-labeled outgoing port. DAC- and amplifier-less control of the carrier-injection Si-Pho switches is demonstrated, revealing successful switching of 10Gb/s data packets with BF-based forwarding information changes taking place at a time-scale that equals the duration of four consecutive packets.

10109-33, Session 7

Converged photonic data storage and switch platform for exascale disaggregated data centres

Richard C. Pitwon, Kai Wang, Alex Worrall, Seagate Systems (UK) Ltd. (United Kingdom)

In order to sustain exponential global digital data growth, exascale Cloud data centre providers are turning to disaggregated schemes, such as OpenCompute, in which geographically distributed computing and storage resources from across the whole data centre can be dynamically assigned to tasks as required, rather than being restricted to a geographically localized pool of dedicated resources, as is the case with colocation centres. This has the potential to substantially reduce power consumption and total cost of ownership. Optical links would be instrumental in providing direct, high bandwidth links to geographically diverse resources acting in unison. While current schemes target higher switching tiers in the data centre, the continuing depreciation in transceiver cost is fuelling the migration of optical interconnect deeper into the cost sensitive high volume, low margin equipment under the Top-of-Rack including data storage and switch platforms.

We report on a converged optically enabled Ethernet storage, switch and compute platform, which could support future disaggregated architectures, but goes further than traditional models in that it provides deeply migrated optical links right down to the storage and switch subsystem nodes themselves. The platform comprises optically enabled Ethernet switch controllers, an electro-optical midplane with a complex 196 fibre PrizmMT terminated fibre-flexplane and optically enabled end node slots. We demonstrate system level performance using optically enabled Ethernet disk drives and micro-servers across long direct optical links.

10109-34, Session 8

Thermo-optic tunable gratng structure for both coupler and radiator applications in silicon

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The grating structures in silicon photonics are treated as key devices for light coupling in wafer level test and optical packaging with its compactness and ease of fabrication. The grating structures are also used as optical phased array antennas for the LiDAR applications. However, the central wavelength of grating indicating a maximum light coupling efficiency or radiation efficiency is so strictly determined by structural parameters that it limits operational range. To extend the operational range, we propose tunable grating structures implemented by change of the effective refractive index based on thermo-optic effect in silicon. For resistive heating, pin or pn junction was formed in the grating region and surrounding region was thermally isolated. The grating structures were formed at both ends of waveguide with a width of 10?. The devices were fabricated on SOI wafer with a thickness of top silicon thickness of 220 nm through CMOS-compatible processes. Fabricated tunable gratings were characterized by fiber-to-fiber measurement and Fourier-imaging system with a variation of bias voltage applied to the heater. From a pin type structure showing the best data, we achieved a wide tuning of the central wavelength with a tuning range of 40nm and an efficiency of 0.41nm/mW. When this tunable grating structure is applied in the radiator of the optical phased array, the radiation angle was actively manipulated in a range of 3? in the longitudinal direction.

10109-35, Session 8

Electro-optic polymer ring-resonator-based reconfigurable logic devices for optical interconnects utilizing imprinting and inkjet printing

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An optical reconfigurable logic device is an optical equivalent of an FPGA, and all the basic digital logic functions can be realized. A tremendous advantage that the optical scheme has over the conventional electronic scheme is the elimination of gate latency and simultaneous availability of a logic function and its complementary at the output, which makes this approach extremely efficient. In this paper, an electro-optic polymer-based high-performance reconfigurable logic system is proposed. Compared to silicon, electro-optic polymers have the advantages of 1) large electro-optic coefficient and ultra-fast response speeds, and 2) easy solution-based processability, thus ultra-high speed logic systems on flexible and rigid substrates are possible. Although most polymer materials can be spun on to form a uniform layer, their patterning into a waveguide often relies on the use of reactive-ion etching (RIE), which is not only an expensive process, but also deteriorates the surface quality, thus negating any advantage provided by polymeric material systems. To address this problem, we utilize all-additive "printing" process comprising of nanoimprint lithography and ink-jet printing for developing low-loss and high surface-quality systems. The ring resonator, demonstrated with Q-factor of 20,720 and switching speed of 1 MHz, is used as an integral component of the logic device. Utilizing different configuration architectures of ring resonators, polymer-based optical logic gates are proposed. The R2R compatible printing processes will enable high-rate, low-cost, and large-area development of these devices on flexible as well as on rigid substrates, thus enabling high-performance integrated polymer based optical interconnect systems.

10109-36, Session 8

Rich third-order nonlinearity of graphene oxide films towards all-optical communications *(Invited Paper)*

Han Lin, Xiaorui Zheng, Baohua Jia, Swinburne Univ. of Technology (Australia)

Third-order nonlinear optical materials play a significant role in the field

of all-optical communications owing to their unprecedented ability to modulate light with an ultrahigh speed. Seeking innovative high third-order nonlinear materials represents an on-going research topic. The discovery of the two-dimensional graphene and its derivative, graphene oxide (GO), has attracted tremendous interest due to their unique physical and chemical properties, which promise new solutions to outstanding challenges [1,2]. In particular, the nonlinear optical properties of GO have been extensively investigated and the rich and giant third-order nonlinear responses have been demonstrated [3]. However, experimental investigation on the Kerr nonlinearity has only been conducted in GO solutions or composites, which are challenge to use for solid-state integrated photonic devices.

In this paper, the Kerr nonlinear responses are investigated from optical quality GO thin films, which are highly integratable with photonic chips. Giant third order nonlinearity that is three orders of magnitude larger than those in the previous reports were observed, leading to a giant nonlinear figure of merit (FOM) crucial for functional nonlinear device design. Our results have not only explored the rich nonlinear responses of GO films, but also demonstrated the tunability of their nonlinear properties, in particular nonlinear refraction, n2, for highly integrated nonlinear photonic applications on a thin film [4,5].

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[2] Light Sci. Appl. 2 , e92 (2013).

[3] Nanotechnology 21, 415203 (2010).

[4] Adv. Mater 26, 2699 (2014).

[5] Appl. Phys. Letts, 107, 031112 (2015).

10109-37, Session 8

Definitive difference between the even and odd modes of photonic crystal dual nanobeam cavities

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Photonic crystal nanobeam cavities can be used for applications such as wavelength filtering, all-optical switching, optomechanics, and nonlinear signal processing. Two nanobeam cavities in close proximity of each other can strongly couple to each other and produce two modes with even and odd transverse symmetry. These two modes exhibit some fundamental differences in quality factors and resonant wavelength shift. The origin of such difference stems from the leaky field in the airgap between the two nanobeams. For the even mode, a significant fraction of the optical field penetrates into the airgap. This causes a large-dependence of the resonant wavelength of the even mode on the airgap width. It also results in a lower quality factor. For the odd mode, less field penetrates into the airgap. As such, the resonant wavelength is less sensitive to the airgap width, and the quality factor is higher. Detailed simulation and experimental results will be presented to support these theoretical considerations. The implication of these characteristics in filtering and all-optical switching will be discussed.

10109-38, Session 9

Advanced R&D addressing future trends in integrated silicon photonics *(Invited Paper)*

Charles Baudot, STMicroelectronics (France)

Silicon photonics is a topic that draws much attention in the semiconductor industry. Even if mass production did not take off yet, there is a shared feeling that this technology will be full of promises. Silicon photonics is already addressing solutions in data-communication area and can potentially address new industrial segments such as long haul telecommunication cables, smart detectors, chemical sensors or even consumer products such as next generation computer peripheral cables. Consequently, STMicroelectronics is concentrating efforts in launching silicon photonic research activities that explore innovative solutions for future market demands. With a smart transition from discrete photonics to integrated photonics, ongoing developments in silicon photonics include the ability to co-integrate different materials within the same platform. Typically, epitaxially grown germanium is used to fabricate photodetectors. Moreover, a vast activity is also devoted at integrating III-V laser sources within the integrated circuit. Currently, various configurations are under evaluation to integrate a laser source within the silicon photonic chip. Furthermore, alternative non-metallic materials are also assessed to fabricate complementary passive devices. The rationale is to consider possible processes and designs to improve electrical power consumption budget, reduce optical transmission losses, achieve low cost production and introduce new functions within photonic systems.

Developments made in the framework of COSMICC European project aim at demonstrating few pJ/bit data transmission for a 4-channel coarse wavelength division multiplexing transceiver bearing a data rate of 56 Gbps NRZ per channel. The demonstrator will make use of current and projected developments made by both STMicroelectronics and collaborators.

10109-39, Session 9

Thick-SOI Echelle grating for any-to-any wavelength-routing interconnection in multi-socket computing environments

George Dabos, Aristotle Univ. of Thessaloniki (Greece) and Ctr. for Interdisciplinary Research and Innovation, Aristotle Univ. of Thessaloniki (Greece); Stelios Pitris, Charoula Mitsolidou, Theonitsa Alexoudi, Dimitrios Fitsios, Aristotle Univ. of Thessaloniki (Greece); Matteo Cherchi, Mikko Harjanne, Timo Aalto, VTT Technical Research Ctr. of Finland Ltd. (Finland); George T. Kanellos, Nikos Pleros, Aristotle Univ. of Thessaloniki (Greece)

As data centers constantly expand, electronic switches are facing the challenge of enhanced scalability and the request for increased pin-count and bandwidth. Photonic technology and wavelength division multiplexing have always been a strong alternative for efficient routing and their potential was already proven in the telecoms. CWDM transceivers have emerged in the board-to-board level interconnection, revealing the potential for wavelength-routing to be applied in the datacom and an AWGR-based approach has recently been proposed towards building an optical multi-socket interconnection to offer any-to-any connectivity with high aggregated throughput and reduced power consumption.

Echelle gratings have long being recognized as the multiplexing block exhibiting smallest footprint and robustness in a wide number of applications compared to other alternatives such as the Arrayed Waveguide Grating. Such filtering devices can also perform in a similar way to cyclical AWGR and serve as mid-board routing platforms in multi-socket environments. In this communication, we present such a 3x3 Echelle grating integrated on thick SOI platform with aluminum-coated facets that is shown to perform successful wavelength-routing functionality at 10Gb/s. The 3dB-bandwidth of the channels was 4.5nm and the free spectral range was 90nm. The echelle was evaluated in a 2x2 wavelength routing topology, exhibiting a power penalty of below 0.4dB at 10-9BER for the C-band. Further experimental evaluations of the platform involve commercially available CWDM datacenter transceivers, towards emulating an optically-interconnected multi-socket environment traffic scenario.

10109-40, Session 9

Hybrid Integration of Laser Source on Silicon Photonic Integrated Circuit for low-cost Interferometry Medical Device

Matthieu Duperron, Lee B. Carroll, Marc Rensing, Sean

Collins, Yan Zhao, Tyndall National Institute (Ireland); Yanlu Li, Roel G. Baets, Univ. Gent (Belgium); Peter A. O'Brien, Tyndall National Institute (Ireland)

The cost-effective integration of laser sources on Silicon Photonic Integrated Circuits (Si-PICs) is a key challenge to realising the full potential of on-chip photonic solutions for telecommunication and medical applications. Hybrid integration offers particularly high-yields solutions, using only "known-good" laser-chips, with simple free-space micro-optics to transport light from the laser to the grating-coupler on the Si-PIC.

In this work, part of the CARDIS H2020 project, we describe the development of a passively assembled micro-optical bench (MOB) for the hybrid integration of a 1550nm 20MHz linewidth laser-diode on a Si-PIC, for an on-chip interferometer based medical device. Insertion-losses to (and back-reflections from) a standard grating-coupler (15um x 12um) on the Si-PIC are minimized by using a dual-lens MOB design that optimized the spot-size and reduces optical aberrations of the free-space laser beam on the coupler, and facilitates the inclusion of a sub-millimeter latched-garnet optical-isolator. The 20dB suppression from the isolator helps ensure the high frequency stability of the light source, while the high thermal conductivity of the AlN MOB submount (300 W/m.K) and the close integration of a thermistor ensure stabilised thermo-electric cooling of the laser-diode, which minimises low-frequency drift during the approximately 10s point-of-care measurement.

The dual-lens MOB is compatible with cost-effective passively-aligned mass-production, and can be optimised for alternative PIC-based applications.

10109-41, Session 9

III-V/Si hybrid laser arrays using back-end-of-the-line (BEOL) integration *(Invited Paper)*

Xuezhe Zheng, Oracle Corp. (United States)

Creating arrays of efficient optical sources to enable dense integration of silicon photonic transceivers with silicon VLSI circuits remains a challenge. We review manufacturing strategies and challenges for back-end-of-line integration of tunable, external-cavity lasers using edge-coupled and surface-normal coupled integration approaches showing that such laser arrays can be manufactured with a fab-less model. We demonstrate, for the first time, hybrid laser arrays using both integration approaches, highlighting performance and design differences. We also discuss challenges and opportunities for each method and present experimental techniques to reduce alignment tolerance and improve laser stability and mode-control.

10109-42, Session 9

Hybrid photonic crystal lasers *(Invited Paper)*

Liam O'Faolain, Univ. of St. Andrews (United Kingdom)

Energy efficient Wavelength Division Multiplexing (WDM) is the key to satisfying the future bandwidth requirements of datacentres. As the silicon photonics platform is regarded the only technology able to meet the required power and cost efficiency levels, the development of silicon photonics compatible narrow linewidth lasers is now crucial. We discuss the requirements for such laser systems and report the experimental demonstration of a compact uncooled external-cavity mWatt-class laser architecture with a tunable Silicon Photonic Crystal resonant reflector

10109-43, Session PWed

Cost-effective 25-Gbps active optical cable incorporating a plastic micro-optic module

Yong-Geon Lee, Sang-Shin Lee, Kwangwoon Univ. (Korea, Republic of); Yung-Sung Son, Optomind Inc. (United States)

An active optical cable (AOC) of 25-Gbps small form-factor pluggable (SFP) configuration, which capitalizes on a plastic micro-optic module, has been proposed and realized to feature a high structural tolerance. The AOC consists of a transmitter (Tx), a receiver (Rx), a graded-index plastic optical fiber, a vertical cavity surface emitting laser (VCSEL), and a photodetector (PD). An alignment fixture, which is based on a prism and cover that are integrated with a collimating/focusing ashperic lens, is incorporated into both the Tx and Rx. In particular, a pair of precisely controlled reference holes are inherently inscribed in a printed circuit board, whereby the VCSEL and PD are mounted. The optical coupling from the VCSEL to PD is efficiently established via the pick-and-place scheme in a cost effective manner, with the assistance of the reference holes. For the manufactured modules for the Tx and Rx, which is approximately 1.5 mm thick, the achieved 3-dB alignment tolerance was 20 ?m for the VCSEL and PD. To scrutinize the high-speed performance of the fabricated AOC, the prepared modules were tested to transmit a 2^31-1 pseudorandom bit sequence (PRBS) signal over a 10-m long ribbon POF. It was confirmed that the AOC could fulfill an error free data transmission at 25 Gbps, exhibiting slight variations of less than 0.1 dB in the optical coupling at the ambient temperature.

10109-44, Session PWed

Modeling of all-optical 3x8 line decoder using optical Kerr effect in plasmonic metal-insulator-metal waveguides

Lokendra Singh, Amna Bedi, Santosh Kumar, DIT Univ. (India)

In today's scenario, all research efforts are made towards all-optical phenomenon to achieve higher bandwidth and data rates. Hence, an all optical circuit of 3?8 line decoder using plasmonic metal-insulator-metal (MIM) waveguides due to their unique property of confining the surface plasmons (SPs) to deep subwavelength scale is modelled and analyzed. To attain all-optical phenomenon, Kerr material has been used in MIM waveguides. Study and analysis of proposed device is done by using finite difference time domain (FDTD) method and MATLAB simulation work.

10109-45, Session PWed

Key parameters for obtaining graded-index perfect circular cores in polymer waveguides using the Mosquito method

Yuki Saito, Koji Fukagata, Takaaki Ishigure, Keio Univ. (Japan)

In this paper, we present the key parameters of the core and cladding materials for obtaining polymer optical waveguides with graded-index (GI) perfect circular cores which allows low propagation and coupling losses.

We have proposed a unique fabrication method named the Mosquito method for multimode polymer optical waveguides with GI cores to be applied to board-level optical interconnection. In the Mosquito method, GI waveguides with circular cores are fabricated by dispensing a liquid-state core monomer from a syringe needle into a liquid-state cladding monomer. However, perfect circular cores are not always obtained when various combinations of the core and cladding monomers are applied to the Mosquito method.

So, in this paper, we focus on the viscosity of the liquid-state monomers and the circularity of the cores in the fabricated waveguides is evaluated. Then, it is found that the core shape depends on the viscosity ratio of the core to the cladding monomers. When the viscosity ratio is lower, tear-drop shaped cores are likely to be formed, while the higher viscosity ratio leads to heart-shaped cores. Using the monomers whose viscosity ratio is in an appropriate range, perfect circular or slightly elliptic cores are likely to be formed. In addition, we find that even though the viscosity ratio is higher than the optimum range, circular or elliptic cores are successfully fabricated if a curved needle is used. We also discuss in this paper about the propagation and coupling loss sensitivity to the deformation of core shape from the perfect circle.

10109-46, Session PWed

Indium titanium oxide-based plasmonic Mach-Zehnder modulator

Abdalrahman Abdelhamid, Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

On the way of seeking faster computers, electrical interconnects speed and heat problems have to be solved. Optical interconnects can be the solution if it is enabled to pass the footprint and power consumption limits required by the electronics. A plasmonic mach-zehnder modulator is being studied numerically, this work is a step forward towards achieving a compact modulator. The arms are made of metal-dielectric-Indium Tin Oxide (ITO) - silicon-metal. One of the arms of the modulator acts as an electro-absorption modulator (imaginary index modulator). The other arm modulates the real and imaginary parts of the refractive index of the ITO (real index modulator), as to create similar losses to the imaginary index modulator arm, while creating a large difference in the effective index between the two arms. The difference between the arms is in the dielectric, the electro-absorption arm has a dielectric with lower refractive index than the real modulator arm. The difference in the effective index between the arms of the modulator is more than 0.5, which results in arm length less than 1.55μm at a voltage less than 2V. This design results in a voltage length product of about 3Vμm, which is more than an order of magnitude smaller than the reported values. Also capacitance and power consumption is to be far lower than the reported values. Low insertion loss is expected due to the low length plasmonic arms, and in turns, high extinction ratio.

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10110-1, Session 1

Simulation of waveguide-based near-to-eye displays *(Invited Paper)*

Daniel Asoubar, LightTrans International UG (Germany); Christian Hellmann, Wyrowski Photonics UG (Germany); Hagen Schweitzer, LightTrans International UG (Germany); Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany)

Various existing or upcoming near-to-eye displays consist of a thin waveguide for guiding light from a display or laser scanner to the human eye. On the waveguide holographic or surface gratings are located for coupling light into and out of the waveguide as well as expanding the light. For the realistic simulation of such near-to-eye displays the propagation of entire wavefronts through the waveguide as well as stray light caused by zero and higher diffraction orders of the gratings must be analyzed. In this presentation both effects are modeled by Field Tracing, which enables a fast physical optics analysis of near-to-eye displays. It is shown that this approach includes all relevant electromagnetic field effects like speckle, interferences, spatial and temporal coherence as well as polarization. For an accurate simulation of the grating response we apply locally a rigorous grating modeling technique, i.e. the Fourier modal method (FMM). This ensures that diffraction efficiency, polarization effects and phase of diffraction orders can be taken into account correctly although they strongly depend on both, the wavelength and the incident angle. Simulation results of several simple near-eye displays are shown to demonstrate the flexibility and performance of the discussed modeling concepts. All simulations are based on the software VirtualLab Fusion.

10110-2, Session 1

Modeling diffractive effects due to micro-lens arrays on liquid crystal panels in projectors

Daniel Herrmann, Chenglin Xu, Mayank Bahl, Jake Jacobsen, Synopsys, Inc. (United States)

The components in optical projectors are becoming increasing smaller due to the need for increased output resolution and the desire for small form-factor devices. One such component is Liquid Crystal (LC) panels, that utilize periodic micro-lens arrays, which become more sensitive to diffractive effects as the period becomes near/sub wavelength. This paper explores the diffraction effects within these systems through numerical modeling. Traditionally Ray tracing technique has traditionally been used for analyzing projection systems and has led to significant improvements in illumination uniformity and efficiency. However, increasingly complex projector designs that incorporate smaller geometric features like micro/nano lens arrays, including coherent diffraction and interference effects arising from such structures, cannot be handled by ray-tracing approaches alone. Rigorous electromagnetic (EM) wave optics based techniques, such as finite-difference time-domain (FDTD) and rigorous coupled wave analysis (RCWA) which solve Maxwell's equations must be used. These rigorous EM techniques, however, have difficulty in analyzing the larger structures due to computational resource limitations. We use a mixed-level optical simulation methodology which unifies the use of rigorous EM wave-level and ray-level tools for analyzing projector performance. This approach uses rigorous EM wave based tools to characterize the micro-lens array through a Bidirectional Scattering Distribution function (BSDF) file. These characteristics are then incorporated into the ray-tracing simulator for the illumination and imaging system design and to obtain the overall performance. Such mixed-level approach allows for comprehensive modeling of the optical characteristic of projectors, including coherent effects, and can potentially lead to more accurate performance than that from individual modeling tools alone.

10110-3, Session 1

Automatic correction of diffraction pattern shift in a pushbroom hyperspectral imager with a piezoelectric internal line-scanning unit

Mohammad Abdo, Karlsruher Institut für Technologie (Germany); Erik Förster, Patrick Bohnert, Carl Zeiss Jena GmbH (Germany); Moritz Stürmer, Institut für Mikrosystemtechnik, Univ. of Freiburg (Germany); Vlad Badilita, Karlsruher Institut für Technologie (Germany); Robert Brunner, Ernst-Abbe-Hochschule Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Ulrike Wallrabe, Institut für Mikrosystemtechnik, Univ. of Freiburg (Germany); Jan G. Korvink, Karlsruher Institut für Technologie (Germany)

Hyperspectral imaging (HSI) is an emerging non-invasive, non-destructive, and contact-free analysis technique that provides spatially-resolved spectral information about a target, and therefore has found applications in different fields including agriculture, medical diagnostics, industrial sorting, and environmental monitoring. Among the methods for acquiring hyperspectral data is the "pushbroom" technique, in which spectral information is acquired for each line of the image by means of spatial scanning. This technique requires relative motion between the target and the imaging system, often introduced using an external scanning stage or a conveyor belt, which increases the equipment cost and limits the application scenarios.

In this work, we address this by introducing a pushbroom HSI system with an internal piezoelectric line-scanning unit and automatic correction of diffraction pattern shift. A front lens group brings the scene to an intermediate image plane where a slit aperture of 20 μm width is positioned. Mounted on a piezoelectric linear motor with a position encoder, the slit can be laterally scanned across the image plane with a step resolution of 100 nm. Each slit position captures one line of the image, for which the spectral information is generated using a transmission blazed diffraction grating, and recorded using a CCD camera. However, for each line, the incidence angle at the grating will be tilted with respect to the optical axis, leading to a shift in the first order diffraction angle, and consequently a shift in diffraction pattern on the CCD detector. We demonstrate an automatic method to compensate for this shift by using a stepper motor-controlled rotating arm to reposition the camera relative to the slit position.

10110-4, Session 1

All plastic ultra-small size imaging lens unit fabrication and evaluation for endoscope

Kenta Ishii, Dai Okamoto, Makoto Ushio, Hidetoshi Tai, Atsuhiko Nishihara, Kimio Tokuda, Shinsuke Kawai, Seiichiro Kitagawa, Nalux Co., Ltd. (Japan)

There is demand for small-size lens units for endoscope and industrial applications. Polished glass lenses with a diameter of 1~2mm exist, however plastic lenses similar in size are not commonplace. For low-cost, light-weight, and mass production, plastic lens fabrication is extremely beneficial. Especially, in the medical field, there is strong demand for disposable lens unit for endoscopes which prevent contamination due to reuse of the lens. Therefore, high mass producible and low cost becomes increasingly important. This paper reports our findings on injection-molded ultra-small size plastic lens units with a diameter of 1.3mm and total thickness of 1.4mm.

We performed optical design, injection molding, and lens unit assembly for injection moldable, high imaging performance ultra-small sized lens units. We prioritize a robust product design, considering injection molding properties and lens unit assembly, with feedback from molding simulations reflected into the optical design. A mold capable of high precision lens positioning is used to fabricate the lenses and decrease the variability of the assembly. The geometric dimensions of the resulting lenses, are measured and used in the optical simulation to validate the optical performance, and a high agreement is reported. The injection molding of the lens and the assembly of the lens unit is performed with high precision, and results in high optical performance.

10110-5, Session 1

Design and evaluation of a freeform lens by using a method of luminous intensity mapping and a differential equation

Mahmoud Essameldin, Friedrich Fleischmann, Thomas Henning, Bremen Univ. of Applied Sciences (Germany); Walter Lang, Univ. Bremen (Germany)

Freeform optical systems are playing an important role in the field of illumination engineering for redistributing the light intensity, because of its capability of achieving accurate and efficient results. The authors have presented the basic idea of the freeform lens design method at the 117th annual meeting of the German Society of Applied Optics (DGAO-Proceedings). Now, we demonstrate the feasibility of the design method by designing and evaluating a freeform lens. The concepts of luminous intensity mapping, energy conservation and differential equation are combined in designing a lens for non-imaging applications. The required procedures to design a lens including the simulations are explained in detail. The optical performance is investigated by using a numerical simulation of optical ray tracing. For evaluation, the results are compared with another recently published design method, showing the accurate performance of the proposed method using a reduced number of mapping samples. As a part of the tolerance analyses of the fabrication processes, the influence of the light source misalignment (translation and orientation) on the beam-shaping performance is presented. Finally, the importance of considering the near-filed and the far-field modeling of the light source while designing a freeform lens using the proposed method is discussed.

10110-6, Session 2

Optical stent inspection of surface texture and coating thickness

Carlos Bermudez, Ferran Laguarta, Cristina Cadevall, Sensofar-Tech, S.L. (Spain) and Technical Univ. of Catalonia (Spain); Aitor Matilla, Sensofar-Tech, S.L. (Spain); Sergi Ibañez, Sensofar Medical, S.L. (Spain); Roger Artigas, Sensofar-Tech, S.L. (Spain) and Technical Univ. of Catalonia (Spain)

Stent quality control is a critical process. Coronary stents have to be inspected 100% so no defective stent is implanted into a human body. We have developed a high numerical aperture optical stent inspection system able to acquire both 2D and 3D images. Combining a rotary stage, an area camera with line-scan capability and a triple illumination arrangement, unrolled sections of the outer, inner, and sidewalls surfaces are obtained with high resolution. During stent inspection, surface roughness and coating thickness uniformity is of high interest. Due to the non-planar shape of the surface of the stents, the thickness values of the coating need to be corrected with the 3D surface local slopes. A theoretical model and a simulation are proposed, and measurements with both confocal and white light interferometry are shown in comparison. We have also performed measurements of thickness values with spectroscopic reflectometry to validate our proposed method. Due to the high numerical aperture of the optical system, only certain parts of the stent are in focus, which is a problem for defect detection, specifically on the side walls. In order to obtain fully focused 2D images, an extended depth of field algorithm has been implemented. A comparison between pixel variance and Sobel filtering is shown. To recover the stack image, two different methods are proposed: maximum projection and weighted intensity. Finally, we also discuss the implementation of the processing algorithms in both the CPU and GPU, targeting real-time 2-Million pixel image acquisition at 50 frames per second.

10110-7, Session 2

Determination of the paraxial focal length using Zernike polynomials over different apertures

Tobias Binkele, David Hilbig, Thomas Henning, Friedrich Fleischmann, Hochschule Bremen Univ. of Applied Sciences (Germany)

As will be presented at the SPIE Optics + Photonics 2016, the paraxial focal length, still the most important parameter in the design of a lens, can be described as a limit value of the dependency of the Zernike defocus term on the aperture. In this work, we investigate the dependency of the Zernike polynomials on the aperture size with respect to 3D space. By this, conventional wavefront measurement systems that apply Zernike polynomial fitting (e.g. Shack-Hartmann-Sensor), can be used to determine the paraxial focal length, too.

Since the Zernike polynomials are orthogonal over a unit circle, the aperture used in the measurement has to be normalized. By shrinking the aperture and keeping up with the normalization, the Zernike coefficients change. The relation between these changes and the paraxial focal length are investigated. The dependency of the focal length on the aperture size is derived analytically and evaluated by simulation and measurement of a strong focusing lens.

The measurements are performed using experimental ray tracing and a Shack-Hartmann-Sensor. Using experimental ray tracing for the measurements, the aperture can be chosen easily. Regarding the measurements with the Shack-Hartmann-Sensor, the aperture size is fixed. Thus, the Zernike polynomials have to be adapted to use different aperture sizes by the proposed method. By doing this, the paraxial focal length can be determined from the measurements in both cases.

10110-8, Session 2

Highly sensitive measurement of submicron waveguides based on Brillouin scattering

Adrien Godet, Abdulaye Ndao, Jean-Charles Beugnot, Thibaut Sylvestre, Kien Phan Huy, Univ. de Franche-Comté (France)

Fabrication and characterization of submicron waveguides is one of the major challenges in photonics. It finds various applications as photonic sensors, micro-resonator coupling, non-linear optic or plasmonic devices. The characterization of the dimensions of those nanoscale objects is usually performed by scanning electron microscopy (SEM). Here we report a novel measurement technique based on Brillouin backscattering, a nonlinear acousto-optic interaction where light interacts with acoustic vibrations of the waveguide. Through this interaction, part of the light is reflected and frequency shifted. The measurement and analysis of the backscattered light spectrum shows various resonance peaks and theoretical investigation has shown that the measured Brillouin spectrum is a signature of the waveguide geometry. Our measurement method was applied to several fiber tapers with diameter ranging from 700 nm to 3 microns. Results were compared

to SEM images and numerical simulations with a very good agreement achieving similar sensitivity.

10110-9, Session 2

Capabilities and challenges in transferring the wavefront-based alignment approach to small aperture multi-element optical systems *(Invited Paper)*

Reik Krappig, Robert Schmitt, Fraunhofer-Institut für Produktionstechnologie IPT (Germany)

Present alignment methods already have an accuracy of some microns. Nevertheless, they suffer decisive drawbacks, such as the necessity of an iterative process, stepping through all optical surfaces of the system when using autocollimation telescopes. In contrast to these limitations, the wavefront based alignment offers an elegant approach to potentially reach sub-µm accuracy in the alignment of small aperture multi-element optical systems like microscope or camera objectives.

However, the practical use of these capabilities in corresponding alignment machines needs to take real sensor behaviour into account. This publication will especially elaborate on the influence of the sensor properties in relation to the alignment process. The first dominant requirement is a highly stable measurement, since tiny perturbations in the optical system will have an also tiny influence on the wavefront. Secondly, the lateral sampling of the measured wavefront is supposed to be as high as possible in order to be able to extract higher order Zernike coefficients reliable. The resulting necessity of using the largest sensor area possible conflicts with the requirement to allow a certain lateral displacement of the measured spot, indicating a perturbation. A movement of the sensor with suitable stages in turn leads to additional uncertainties connected to the actuators. Further factors include the SNR-ratio of the sensor as well as multiple measurements, in order to improve data repeatability.

This publication will present a procedure of dealing with all relevant influence factors. Depending on the optical system and its properties the optimal adjustment of these parameters is derived.

10110-10, Session 2

System-level analysis and design for RGB-NIR CMOS camera

Bert Geelen, Nick Spooren, Murali Jayapala, Klaas Tack, Andy Lambrechts, IMEC (Belgium)

This paper presents system-level analysis of a sensor capable of simultaneously acquiring both standard wideband (400-700nm, FWHM: ~75nm collimated light) RGB color channels, as well as an additional NIR channel (central: ~800nm, FWHM: ~30nm collimated light). Parallel acquisition of RGB and NIR info on the same CMOS image sensor is enabled by monolithic pixel-level integration of both a patterned NIR pass thin film filter and patterned NIR blocking filters for the RGB channels. This overcomes the need for a standard camera-level NIR blocking filter to remove the NIR leakage present in standard RGB absorption filters from ~700-1000nm. Such a camera-level NIR blocking filter would inhibit the acquisition of the NIR channel on the same sensor. Thin film filters do not operate in isolation. Rather, their performance is influenced by the system context in which they operate. The spectral distribution of light arriving at the photo diode is shaped a.o. by the illumination spectral profile, optical component transmission characteristics and sensor quantum efficiency. For example, knowledge of a low quantum efficiency (QE) of the CMOS image sensor above 800nm may reduce the filter's blocking requirements and simplify the filter structure. Similarly, knowledge of the incoming light angularity as set buy the objective lens' F/# and exit pupil location may be taken into account during the thin film's optimization. This paper demonstrates how knowledge of the application context can facilitate filter design and relax design trade-offs.

10110-11, Session 3

Double-sideband filter for digital holography

Angel Lizana, Claudio N. Ramírez, Univ. Autònoma de Barcelona (Spain); Claudio C. Iemmi, Univ. de Buenos Aires (Argentina); Juan Campos, Univ. Autònoma de Barcelona (Spain)

Nowadays, digital holographic systems are based on two main optical schemes: off-axis (OA) and inline (IL) holographic systems. In OA set-ups, the reference and the object beams present a relative angle at the registration plane. Thus, a real image of the object can be obtained without the influence of conjugated images by performing a spatial filtering at the reconstructed plane.

IL configurations are less sensitive to vibrations and air flows than OA configurations, but the undesired influence of conjugated images in the final hologram is not avoided. To overcome this limitation, a number of IL based methods have been proposed. One interesting approach is the phase-shifting technique, which leads to efficient holograms for IL applications. However, due to the time-sequential nature of this technique, it is somewhat inappropriate for dynamic processes.

We present a new method, for IL digital holography, based on a double-sideband (DSB) filter. This method not only removes the conjugate images in the reconstruction process but also reduces the distortions that usually appear when using single-sideband filters. Moreover, it is only time-limited by the acquisition time of the CCD camera. Thus, it is suitable for dynamic processes and it was tested for the tracking of micro-particles. To this aim, particle holographic images were obtained by using the DSB method and afterwards processed with digital picture recognition methods, this allowing us to accurately track the spatial position of particles. By using this approach, the instantaneous trajectory and velocity described by glass microspheres in movement were experimentally determined.

10110-12, Session 3

Advances in broadband-integrated optic beam combiners for mid-IR astronomical interferometers

Jan Tepper, Univ. zu Köln (Germany); Romina Diener, Friedrich-Schiller-Univ. Jena (Germany); Lucas Labadie, Univ. zu Köln (Germany); Stefano Minardi, Friedrich-Schiller-Univ. Jena (Germany) and Leibniz-Institut für Astrophysik Potsdam (Germany); Robert R. Thomson, Heriot-Watt Univ. (United Kingdom)

The coming together of astronomy and photonics, recently coined astrophotonics, has triggered the development and improvement of novel photonic technologies, such as the photonic lantern or ultrabroadband fibre Bragg-gratings. In particular, in astronomical interferometry the real-time and simultaneous measurement of the pairwise coherence between multiple apertures requires sophisticated and highly accurate and stable beam combining schemes.

A perfect example of this joint effort is the recent success of the silica-on-silicon technology in delivering an integrated optics (IO) beam combiner for the GRAVITY instrument at the Very Large Telescope Interferometer (VLTI), leading to unprecedented accuracy. Driven by the need of next-generation mid-IR interferometers, we continue following the photonic approach and develop IO beam combiners based on novel materials and writing techniques.

Using 3D Ultrafast Laser Writing we are able to create low-loss (0.25dB/cm) single mode waveguides and evanescent couplers for interferometry in gallium lanthanum sulfide (GLS). For the first time to our knowledge, we present a full characterization of mid-IR IO beam combiners.

We optimized the writing parameters for a perfectly balanced coupler over the L band (3.1-3.6μm) and reveal the intrinsic chromaticity by Fourier transform spectroscopy. Excellent contrasts are measured for unpolarized light at 3.39μm (>98%) over the L band (>95%) and over the M Band (4.5-4.8μm) (>95%). This indicates extremely low differential dispersion and differential birefringence. Finally, we discuss the integration of a fiber-fed 4-telescope beam combiner in consideration of next-generation interferometers, a major step forward in extending the operation of IO in astronomy to a broader wavelength range.

10110-13, Session 3

Locally-resolved characterization of progressive addition lenses by calculation of the modulation transfer function using experimental ray tracing

Gustavo Gutierrez, David Hilbig, Friedrich Fleischmann, Thomas Henning, Hochschule Bremen (Germany)

Due to the exotic freeform surface exhibited by Progressive Addition Lenses, a new characterization approach that takes into account the projection of the eye pupil over the lens is required. In this work, a locally resolved description of the performance of the lens has been obtained by calculating the Modulation Transfer Function (MTF) for uniformly spaced subaperture positions. This quality metric is conveniently suitable to characterize imaging systems, because it describes the contrast resolving capabilities of the lens as a function of the spatial frequency. In addition, it is independent of the judgment of the test engineer.

The MTF has been indirectly calculated using Experimental Ray Tracing, by extracting the values of the ray slopes of each subaperture from the complete ray traced data. By following this procedure, two-dimensional maps are generated using two different criteria. The first criterion is based on the determination of the normalized spatial frequency where the MTF has been reduced by 50%. The second one uses a simplified Strehl ratio. Also, the results for different subaperture diameters are obtained without the need for changing the setup or repeating the measurements.

10110-14, Session 3

Optical coherence tomography for non-invasive examination and conservation of cultural heritage objects

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Optical coherence tomography (OCT), a three-dimensional (3D) imaging modality with microscopic resolution, has found clinical applications in ophthalmology and interventional cardiology. Recently, OCT has been applied in the field of cultural heritage conservation. OCT acquires depth resolved profile of the sample in a noncontact manner, and therefore has the potential to become a powerful alternative for invasive examination of oil paintings, particularly for celebrated masterpieces by great artists in the history. Depth resolved OCT signals can be used to reveal surface or subsurface microscopic damages to the artwork or the invisible underdrawings beneath the superficial layers. However, OCT has small field of view (FOV) while oil paintings are macroscopic objects. In addition, OCT images inevitably suffers from speckle noise that reduces image contrast and blurs fine image features. To address these limitations, we developed an OCT system for large FOV high definition (HD) imaging. A spectral domain OCT system with 7.5?m axial resolution and 30?m lateral resolution was used. To achieve large FOV, we translated the sample using a pair of high-precision linear motors and performed sequential volumetric imaging on adjacent, non-overlapping regions. To reduce the speckle noise, we implemented a novel image processing algorithm based on adaptive wavelet domain thresholding. C++ software was developed for OCT data acquisition, real-time signal processing, automatic motor control and image display. We imaged oil paintings (15cm X 15 cm in dimension) with an approximately 5-minute scanning time. The surface terrain and subsurface microarchitecture of the paintings could be characterized and visualized.

10110-16, Session 4

Infrared: the next big thing in automotive sensors? *(Invited Paper)*

Thierry Robin, Jacques Cochard, TEMATYS (France)

Advanced Driver Assistance Systems (ADAS) are embedded in cars to increase safety and reduce traffic congestion, and next generation about full autonomous vehicle intends to increase productivity of the driver and whole population of drivers. It is currently one of the most dynamic segments of the car industry, demonstrating an annual growth of around 25%. Photonics in both visible and infrared spectra has a big role to play in this field. This article will present the results of a current study about infrared-enabled ADAS functions. Strong cost's decrease in infrared technologies, active 3D infrared imaging, night vision as well as computational capacities pave the way for increased use for infrared technologies in the car.

10110-17, Session 4

Hyperspectral calibration method For CMOS-based hyperspectral sensors

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Imec has developed a process for the monolithic integration of optical filters on top of CMOS image sensors, leading to compact, cost-efficient and faster hyperspectral cameras. Imec developed both mosaic (4x4 VIS 470-620 nm range and 5x5 VNIR 600-1000 nm) and linescan sensors (LS100 100+ bands 600-1000 nm and LS150 150+ bands from 475-925 nm) based on CMOSIS CMV2000 image sensor.

Variability in responses due to the monolithic integration of optical filters on the image sensors makes spectral correction a challenge. Solving this problem is relevant to all applications, but crucial where multiple cameras are required (e.g. food inspection) or where cameras have to be replaced without additional calibration steps (such as classifier re-training).

The initial step to address the issue is to individually calibrate the spectral response of each sensor using a monochromator setup (possibly at both sensor and system level). Then proper selection of the sensors will simplify the problem (e.g. by choosing sensors having the closest possible responses). A standard constrained linear least-squares is used to obtain a stable correction matrix from the sensor response and camera model (accounting for illuminant, rejection filters, etc...).

Simulation and experimental results are shown for multiple sensors, different illuminants and collimated light or through lens. Reference targets (colored Spectralon) are scanned and spectrally corrected to illustrate that proper calibration can compensate for sensor variability.

10110-18, Session 4

Optical frequency-domain reflectometry using multiple wavelength-swept elements of a DFB laser array

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Optical frequency-domain reflectometry (OFDR) is a distance measurement technique with significant sensitivity and detector bandwidth advantages over normal time-of-flight methods. Although several swept-frequency laser sources exist, many exhibit short coherence lengths or require precision mechanical tuning components. Semiconductor distributed feedback lasers (DFBs) are advantageous as a long-range coherent OFDR source because they exhibit a narrow linewidth and can be rapidly frequency-swept simply via injection current modulation. However, the maximum wavelength sweep range is thermally limited. Here, we present a novel high resolution OFDR technique that uses a compact, monolithic 12-element DFB array to create a continuous, gap-free sweep. The center wavelengths of the DFBs in the array are equally spaced throughout the 1525 nm to 1565 nm communications C-band. Each DFB is sequentially swept over 3.5nm at a 10^15 Hz/s rate using a shaped current pulse, ensuring spectral overlap between each element. The absolute wavelength of each DFB during the frequency sweep is determined using the absorption peaks of a 25 Torr hydrogen cyanide gas cell and an auxiliary interferometer. The frequency swept spectra of the 12 DFBs are combined to achieve an effectively continuous 40nm total wavelength excursion. A demonstration OFDR system utilizing this DFB array swept source is shown to resolve the surfaces of a 50 micron-thick fused silica etalon at a distance of 1m.

10110-19, Session 4

Optical coating uniformity of 200mm (8”) diameter precut wafers

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Automated spectroscopic profiling (mapping) of a 200 mm diameter near infrared high reflector (centered at 1064 nm) are presented. Spatial resolution at 5 mm or less was achieved using a 5 mm x 1.5 mm monochromatic beam. Reflection changes of 1.0% across the wafer diameter were observed under s-polarized and p- polarized conditions. Redundancy was established for each chord by re-measuring the center of the wafer and reproducibility of approximately <0.1% was demonstrated by duplicate measurements. These measurements demonstrate informative spatial spectroscopic information can be obtained on large diameter samples.

Multi-angle Photometric Spectroscopy (MPS) was used to measure the reflectance and transmittance of a sample across a range of angles (?i) at near normal angles of incidence (AOI). A recent development by Agilent Technologies, the Universal Measurement Spectrophotometer (UMS) combines both reflection and transmission measurements from the same patch of a sample’s surface in a single automated platform for angles of incidence in the range 5°≤|?i|≤85° (i.e. angles on either side of beam normal noted as +/-).

We describe the use of MPS on the UMS with rotational (?) and vertical (z) sample positioning control. MPS(?i,??z) provides for automated unattended multi-angle R/T analysis of at 200 mm diameter samples with the goal to provide better spectroscopic measurement feedback into large wafer manufacturing to ensure yields are maximized, product quality is better controlled and waste is reduced before further down stream processing.

10110-20, Session 5

Ultra-compact imaging plate scanner module using a MEMS mirror and specially-designed MPPC

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Computed radiography (CR), one of the most useful methods for dental imaging and nondestructive testing, uses a phosphor imaging plate because it is flexible, reusable, and inexpensive. Conventional imaging plate scanners utilize a galvanometer or polygon mirror as a scanning device and a photomultiplier as an optical sensor. Now, MEMS technology is providing silicon-based devices with the potential to replace these discrete devices and sensors. Using these MOEMS devices, we constructed an ultra-compact imaging plate scanner whose volume is less than 1000 cc.

Our extremely compact plate scanner utilizes a module that is composed of a one-dimensional MEMS mirror, a long multi-pixel photon counter (MPPC) combined with a specially designed wavelength filter, and a rod lens. The MEMS mirror is of the non-resonant electromagnetic type, is 2.6 mm in diameter, and has an optical scanning angle up to ±15°.

The wide dynamic range of CR is maintained using a newly developed MPPC. The MPPC is a sort of silicon photomultiplier and is a high-sensitivity photon counting device. To achieve a wide dynamic range, we developed a long MPPC, which has over 100,000 microcells.

For size reduction and high optical efficiency, we set the MPPC close to an imaging plate across the rod lens. To prevent the MPPC detecting excitation light, which is much more intense than photo-stimulated light, we produced a sharp-cut wavelength filter that has a large angle (±60 deg.) of tolerance.

The constructed scanner module was evaluated through images of a gray chart and a resolution chart.

10110-21, Session 5

3D label-free super-resolution imaging

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Scanning white light interferometry (SWLI) is a label free optical 3D imaging modality with a vertical sensitivity of a few Ångströms (Å). However, as an optical far-field system, laterally it is diffraction limited resolving only down to few hundred nanometers. We overcome this limit by using microspheres that each produces a photonic nanojet. Thus sub 100 nm features can laterally be resolved.

To validate the capabilities of Photonic nanoJet based Interferometry (PJI) we studied measurement techniques capable of sub-100 nm lateral resolution; Super-Resolution SWLI, atomic force microscope (Witech, alpha300 A) working in AC-mode, and scanning electron microscope (Hitachi S4800). We used a recordable Blu-ray™ disc (Verbarim DataLife BD-R 25GB) as sample. A Blu-ray™ disc features a grooved surface topology with heights in the range of 20 nm and with distinguishable sub 100 nm lateral features that are unresolved by diffraction limited optics.

We achieved agreement between all three measurement devices across lateral and vertical dimensions.

10110-22, Session 5

Round Robin test on bio-imaging transfer standard for 3D optical profilers

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Helsinki (Finland); Niklas Sandler, Åbo Akademi Univ. (Finland); Edward Hæggström, Univ. of Helsinki (Finland); Carlos Bermudez, Roger Artigas, Sensofar-Tech, S.L. (Spain); Ivan Kassamakov, Univ. of Helsinki (Finland)

A stair case height Bio-Transfer-Standard (BTS), developed and produced at the University of Helsinki (UH), was measured in two laboratories. The Round Robin test aims to determine whether BTS works with different optical profilers in different laboratories. First the artifact was measured in UH using a custom-built Scanning White Light Interferometer. Then BTS was measured in Sensofar-Tech, S.L. using an S-neox-type interferometer working either in Phase Shifting Interferometry mode or in Imaging Confocal Microscopy mode. To remove the influence of system calibration, a method of sample shifting and measurement subtraction was used. The BTS features eight polymer steps that are each 4.6 ± 0.1 nm tall on average. All 30 measurements done by 4 different operators at the two different laboratories show good agreement with less than 0.1 nm bias which agrees with theoretical estimations and measurements using surface plasmon resonance technique. The Round Robin test results show applicability of the newly developed bio-imaging transfer standard for 3D optical profilers' calibration

10110-23, Session 5

Using spectroscopy and microscopy to aid in the development and production of fast-moving consumer goods

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We present two applications of spectroscopy to help in the development and production of fast moving consumer goods.

We have developed an instrument which combines time-gated Raman spectroscopy integrated with a fiber optic probe bundle for multi-spectral, multi-point investigation of the distribution of chemicals in complex powder mixtures by separation of their individual Raman spectra. The combined instrumentation design is designed for application in a production environment. This finds particular utility in monitoring the production and potential segregation of washing powders, which require consistency; particularly in the developing world where the efficiency of washing with small amounts of powder is beneficial. However, washing powders, in line with many powder products, have the additional problem of an overwhelming fluorescence signal which is stronger than the Raman signal, arising from the use of artificial whiteners added to such powders. We overcome this through the use of a novel time-gating method separate the "instantaneous Raman signal" from the time delayed fluorescence emission.

We will also present a novel use of confocal microscopy in obtaining high resolution images of fluorescently labelled mascara on eyelashes. This is achieved by mixing mascara with a small amount of fluorescein powder. From these images it is possible to see phenomena such as the bridging of mascara between lashes and to accurately determine the thickness of the mascara. This technique has potential in the testing of mascara by cosmetic companies, and also in monitoring other reactions which involve a waxy substrate which adheres to a curved surface.

The two methods demonstrate how significant commercial challenges can be solved through the application of methods more associated with academic research.

10110-24, Session 5

Development of a high-throughput solution for crystallinity measurement using THz-Raman spectroscopy

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Rapid identification and the quantitative analysis of crystalline content and the degree of crystallinity is vitally important in pharmaceuticals and polymer manufacturing. Crystallinity affects the bioavailability of pharmaceutical molecules and there is a strong correlation between the performance of polymers and their degree of crystallinity. THz-Raman Spectroscopy has enabled the use of low-frequency Raman spectroscopy for determination of crystalline content in materials as a complementary method to X-ray powder diffraction (XRPD). Incorporating motion stages and microtiter plates, we have extended the applicability of THz-Raman technology to high throughput screening applications. We describe a complete THz-Raman well-plate (TR-WP) design, with integrated laser and optical filters that are necessary for detecting low-frequency Raman signals. In powder materials scattering is also affected by particle size and the presence of cavities, which leads to a lack of precision in measuring Raman intensity measurement. We address this problem by spatial averaging using a special motion pattern. This design facilitates precise measurement of low-frequency vibrational/phonon modes, differentiation of polymorphs and other structural characteristics for applications in pharmaceuticals, nano- and bio-materials and the characterization of industrial polymers where XRPD is commonly used.

10110-15, Session 6

Innovative polarization-holographic imaging Stokes spectropolarimeter for astronomy

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An innovative real-time imaging Stokes spectropolarimeter is presented. The main unit of the polarimeter is an integral polarization-holographic diffraction element, which enables the complete analysis of the polarization state of light to be carried out in real time. An element is recorded by a special holographic schema using circularly and linearly polarized beams. As a result it decomposes an incoming light into orthogonal circular and linear diffraction orders. Upon simultaneous CCD intensity measurements of the corresponding points or areas in the diffraction orders and further data reduction through the calibration parameters we get real-time Stokes images of a light source. The further reduction of Stokes images allows to determine detailed polarization state of a light coming from a point or extended space object in a narrow or a wide spectral range. The operating spectral range of the polarimeter is 500-1600 nm with diffraction efficiency equal to 20% at 532 nm, 16% at 635 nm and 2% at 1550 nm. The laboratory calibration tests were obtained with a quasi-monochromatic point size depolarized light source which further were circularly or linearly polarized with known polarization parameters and a degree of polarization near to 100%. The theoretical model of relations between measured intensities in different diffraction orders and Stokes parameters, earlier developed by the authors (Kilosanidze B., Kakauridze G. SPIE Proceedings, vol. 8082-126, 2011), were used to calibrate the polarimeter. The laboratory tests show that the resulting errors are near of 10-2 or better.

10110-25, Session 6

Multi-wavelength mid-IR light source for gas sensing

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Cost effective multi-wavelength light sources are key enablers for wide-scale penetration of gas sensors at Mid-IR wavelength range. Utilizing a novel Mid-IR Si-based photonic integrated circuit filter and wide-band Mid-IR SLEDs, we show the concept of a light source that covers 2.7...3.5 ?m wavelength range with a resolution <1nm. The spectral bands are switchable and tunable and they can be modulated. The source allows for the fabrication of an affordable multi-band gas sensor with good selectivity and sensitivity. The unit price can be lowered in high volumes by utilizing tailored molded IR lens technology and automated packaging and assembling technologies.

The status of the development of the key components of the light source are reported. The PIC is based on the use of thick-SOI technology, SLED is based on AlGaInAsSb materials and the lenses are tailored single crystal, non-oxide glass and heavy metal oxide glasses fabricated by the use of hot-embossing. The packaging concept utilizing automated assembly tools are depicted.

In safety and security applications, the Mid-IR wavelength range covered by the source allows for the detection of several harmful gas components with a single sensor. At the moment, affordable sources are not available. The market impact is expected to be disruptive, since the devices currently in the market are either complicated, expensive and heavy instruments, or the applied measurement principles are inadequate in terms of stability and selectivity.

10110-26, Session 6

Stable wavelength-swept light source designed for industrial applications using KTN beam-scanning technology

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Using a light-beam scanning technology based on a potassium tantalate niobate (KTa1-xNbxO3, KTN) single crystal, a wavelength-swept light source for industrial applications has been constructed. The KTN crystal is placed in an external cavity as an electro-optic deflector to perform wavelength scanning without mechanical operation. Cavity arrangement and mechanism elements are specially designed for long-term stability and environmental robustness. In addition, we have updated the handling of the KTN crystal: a pair of thermistors is used for accurate temperature monitoring, and a 405-nm light is weakly irradiated during the operation for drift suppression. A moderate repetition rate of 20 kHz is selected to suit the practical application. The output of the light source is 6 mW in average power, 1314 nm in central wavelength, and 84 nm in bandwidth. Interference fringes of the light enable us to specify the thickness of a wafer sample by the peak positions of their point spread functions. We have measured the thickness of a silicon wafer to be 3651 μm in the optical length using a reference quartz plate. The distribution of the values obtained is about 0.1 μm (standard deviation). This property is experimentally confirmed to persist continuously at least during 10 days and is reproduced after the light source restarts. Our light source has a remarkable feature that the timing jitter of sweep is extremely low. Thus, we can easily reduce the noise level by averaging several fringes if necessary.

10110-27, Session 6

Layer by layer: complex analysis with OCT technology

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The OCT- Technology allows a topographic imaging in real time with an extremely high geometric spatial resolution and at high speed.

This creates time-dependent interferograms in the beam path a light source. The optical path length is generated by an axial movement of the reference mirror.

The amplitude-modulated optical signal and the carrier frequency are proportional to the scan rate and contains the depth information. Each maximum of the signal envelope corresponds to a reflection (or scattering) within a sample.

The ASP array produces at same time 300 * 300 axial Interferorgamms which touch each other on all sides. The scanning speed is higher by several factors because the signal demodulation for detecting the envelope is not limited by the frame rate of the ASP array in comparison to standard OCT systems.

If an optical signal arrives to a pixel of the the ASP an electrical signal is generated. The background is faded to saturation of pixels by high light intensity to avoid. The sampled signal is integrated continuously multiplied by a signal of the same frequency and two paths whose phase is shifted by 90 degrees from each other are averaged.

The outputs of the two paths are routed to the PC, where the envelope amplitude and the phase calculate a three-dimensional tomographic image.

The OCT technology is presented with examples from industrial practice and complements the theoretical explanations.

10110-45, Session PWed

Fiber optic sensor based in mismatch multimodal interference structure

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The measurement of the level of salinity in the water plays a relevant role in several areas and activities of human being due to it may cause damages in irrigated fields, drinking water and infrastructure. These effects may represent a high economic impact on biodiversity and the human health. Conventional electric methods are essentially based on the property of electrical conductivity, which is a function of the amount of NaCl ions dissolved in a volume of water. However, these systems are susceptible to electrical interference or the risk of a short circuit. Thus, the techniques based on fiber optic devices are attractive due to its low cost, noninvasive, high sensitivity and immunity to electromagnetic interference [1].

In this paper we present the experimental results related to design and construction of a fiber optic sensor capable to detect different concentrations of salt in aqueous solutions. The sensor is based on the effect of multimodal interference (MMI) [2] and it is built by a segment of Non-core multimode fiber (NC-MMF) spliced between two segments single mode fiber (SMF). The segment of the NC-MMF is mismatched transversally 30 μm from axis propagation of SMF. The wavelength transmitted in the system depends of the effective refractive index, effective diameter and the distance of unaligned segment of NC-MMF. When the NC-MMF is surrounded with a saline solution, the constructive interference condition is modified. Thus, the shift in the transmission peak is interpreted as the presence of saltiness water. Preliminary results show is possible to detect concentrations from 0% to 35% w/w solutions both with conventional salt as NaCl. Additional results show the sensor is able to detect other liquid blends for different NC-MMF mismatched distances.

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10110-47, Session PWed

A new technique for the phase difference measurements based on the amplitude estimation

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The paper concerns the problem of accurate measuring the phase difference between two quasi-harmonic optical signals in a real time and presents a new original technique for solving this task. The technique is based upon measuring and analyzing the amplitudes of the following three signals: the two initial quasi-harmonic signals the phase difference of which is to be measured and the third signal that is formed by summing the first two ones. The detailed theoretical consideration of the problem is provided based on the vector representation of the signals with taking into account the stochastic character of the data to be processed due to the inevitable distortions of the signals by the Gaussian noise. The amplitudes of the three signals to be analyzed are shown to obey the Rice statistical distribution. The algorithm of the proposed technique implementation consists in the joint reconstruction of the undistorted signals' amplitudes against the noie background. The required phase difference is further calculated as an angle value from the simple geometrical considerations of a triangle formed by the estimated amplitudes' values. The fundamental distinction of the elaborated phase difference measuring technique consists in the fact that the phase data are obtained as a result of the amplitude measurements only what significantly decreases the demands to the equipment and simplifies the realization of the proposed method in practice. For the amplitudes' estimation the methods of the Rician data analysis are to be applied. The paper provides both the strict mathematical analysis of the problem and the results of the technique's computer simulation. The digital experiments confirm the theoretical conclusions on the feasibility and efficiency of the proposed technique. The possibility of the accurate phase shifts measurements provided by the elaborated method is meaningful for a wide circle of applied tasks to be solved in numerous ranging and communication systems.

10110-49, Session PWed

A pH sensing system using fluorescence-based fibre optical sensor capable of small volume sample measurement

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In this work, a low cost optical pH sensing system that allows for small volume sample measurements was developed. The system operates without the requirement of laboratory instruments (e.g. laser source, spectrometer and CCD camera), this lowers the cost and enhances the portability. In the system, an optical arrangement employing a dichroic filter was used which allows the excitation and emission light to be transmitted using a single fibre thus improving the collection efficiency of the fluorescence signal. The pH sensor in the system uses bromocresol purple as the indicator which is immobilised by sol-gel technology through a dip-coating process. The sensor material was coated on the tip of a 1 mm diameter optical fibre which makes it possible for inserting into very small volume samples to measure the pH. In the system, a LED with a peak emission wavelength of 465 nm is used as the light source and a silicon photo-detector is used to detect the fluorescence signal. Optical filters are applied after the LED and in front of the photo-detector to separate the excitation and emission light. The fluorescence signal collected is transferred to a PC through a DAQ and processed by a Labview-based graphic-user-interface (GUI). Experimental results show that the system is capable of sensing pH values from 5.3 to 8.7 with a linear response of R2=0.968. Results also show that the response times for a pH changes from 5.3 to 8.7 is approximately 150 s and for a 0.5 pH changes is approximately 50 s.

10110-50, Session PWed

Lens-free-imaging-based low-cost microsensor for in-line wear debris detection in lube oils

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The presence of solid particles in suspension in industrial fluids such as lubricants or hydraulic fluids is often a sign of potential present or incoming faults in the machines where they are being used. Therefore, the early detection of these wear particles is a key objective in a proper predictive maintenance program.

The current work describes the application of lens free imaging principles for the detection and classification of wear debris in running lubricant oils.

The potential benefits brought by the lens free microscopy in terms of resolution, deep of field and field of view have been tailored to develop a microsensor for the in-line monitoring of wear debris in oils used in lubricated or hydraulic machines as gearboxes, actuators, engines, etc.

The work presents a laboratory test-bench used for evaluating the optical performance of the Incoherent Lens Free approach applied to the wear particle detection in oil samples.

Additionally, current prototype is presented, which integrates a LED light source, CMOS imager, CPU and detection algorithms, hydraulic connections, measurement cell and the appropriate optical components for setting up the Lens-Free system. The sensor provides the particle number per mL classified in different size ranges as defined by Fluid Cleanliness Standard codes.

The imaging performance is quantified using microestructured samples, as well as by imaging a flow of real used lubricant oils.

Sampling a large fluid volume with a decent spatial resolution, this lens free microsensor could provide a powerful tool at very low cost for in-line wear debris monitoring.

10110-51, Session PWed

A bidirectional EDFA-based long-range interferometric distributed disturbance sensor

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we proposed a bidirectional-EDFA based interferometric sensor to achieve ultra-long range distributed disturbance sensing. In this structure, we used the asymmetric dual Mach-Zehnder interferometry (ADMZI) design to monitor and locate disturbance events. The ADMZI utilized two distributed

feedback (DFB) laser beams and dense wavelength division multiplexing (DWDM) to significantly reduce the influence of Rayleigh backscattering noise, which will seriously deteriorate the signal noise ratio (SNR) in traditional dual Mach-Zehnder interferometer (DMZI) sensor. The sensing range of ADMZI can reach 80km with a SNR of over 10dB.

In this paper we utilized the bidirectional-EDFA to compensate the attenuation of the light intensity, which is the key that limits the sensing range of the ADMZI. With a dispersion compensation algorithm, this sensor can also achieve a good positioning accuracy. A positioning measurement experiment was carried out to verify the effectiveness of the proposed structure. Using a generalized cross correlation based positioning method, the experiment result showed that the sensing range can reach over 200km with a positing accuracy of ±100m. And we theoretically proved that the sensing range is extensible with more bidirectional-EDFAs.

10110-53, Session PWed

Multimodal backside imaging of a microcontroller using confocal laser scanning and optical-beam-induced current imaging

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Microscopy imaging with a single technology is usually restricted to a single contrast mechanism. Multimodal imaging is a promising technique to improve the structural information that could be obtained about a device under test (DUT). Due to the different contrast mechanisms of confocal laser scanning microscopy (CLSM) and optical beam induced current microscopy (OBICM), a combination could improve the detection of structures in integrated circuits (ICs) and help to reveal their layout. While OBIC imaging is sensitive to the changes between differently doped areas and to semiconductor-metal transitions, CLSM imaging is mostly sensitive to changes in reflections.

In this work we present the implementation of OBIC imaging into a CLSM. We show first results using industry standard Atmel microcontrollers (MCUs) with a feature size of about 250nm as DUTs. Analyzing these types of microcontrollers helps to improve in the field of side-channel attacks to find hardware Trojans, possible spots for laser fault attacks and for reverse engineering.

For the experimental results the DUT is placed on a custom circuit board that allows us to measure the current while imaging it in our in-house built stage scanning microscope using a near infrared (NIR) laser diode as light source. The DUTs is thinned and polished, allowing backside imaging through the Si-substrate. We demonstrate the possibilities using this optical setup by evaluating OBIC and CLSM images. We show differences in contrast as well as achievable improvements by combining these techniques.

10110-54, Session PWed

Fiber-optic-based interferometric sensor

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We propose a fiber-optic based liquid sensor that operates in the near infrared range. Sensor structure is composed of the standard single mode fiber as the input and output ports of the optical system. The sensing part of the structure is constructed after etching the cladding then part of the fiber-core followed by metal sputtering. The top and the bottom fiber/metal interface can support two surface plasmon polariton decoupled modes. Once the light source is excited through the input fiber-optic arm, the SPP signals from the two optical branches (the top and bottom interfaces) propagate to the output fiber-optic arm. At the output port both branches interfere with each other and modulate the far-field scattering, then the transmitted signal is to be coupled to fiber. The sensitivity of the structure is measured to be 11500 nm/RIU; this value out performs the sensitivity of other fiber-optic sensors to our knowledge. The figure of merit (FOM) which expresses the overall performance of the sensor was measured to be 140 showing the high performance of the sensor. Single mode fiber sensor is being fabricated using the standard photolithography process followed by subsequent wet-etching and metal coating using Ag sputtering. This fabrication process is simple, cheap and scalable.

10110-55, Session PWed

High-resolution fast-temperature-mapping of a gas turbine combustor simulator with femtosecond infrared laser written fiber Bragg gratings

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Femtosecond Infrared (fs-IR) written fiber Bragg gratings (FBGs), have demonstrated great potential for sensing in extreme environments. This paper presents the fabrication and deployment of several fs-IR written FBG temperature probes, each with more than 40 sensors, for monitoring internal and exhaust temperature gradients of a gas turbine combustor simulator.

For advanced gas turbine engines, accurate measurement at the combustor exit has become increasingly important since demands for higher efficiency and more stringent emission targets drive their operation closer and closer to established limits. The ability to measure temperature under such harsh environments is currently restrained by the lack of sensors and controls capable of withstanding the high temperature, pressure and corrosive conditions present. Thermocouples are most commonly used due to their low cost and simplicity, but where steep temperature gradients exist, their slow response and instrumentation complexity demand alternative solutions. fs-IR FBG sensors have inherent advantages over thermocouples for rapidly measuring high resolution temperature profiles under harsh conditions.

Results of this work include: contour plots of measured internal and exhaust temperature gradients, contrast of FBG measurements with thermocouple data, discussion of deployment strategies, as well as comments on reliability and other important considerations.

10110-56, Session PWed

Cantilever Fabry-Perot optical accelerometer with 45-angled fiber

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The proposed Fabry-Perot optical acceleration sensor is formed by a 45-angled single mode fiber and a commercial SC split ceramic sleeve. The sidewall of the polished fiber and the internal surface of the sleeve forms the Fabry-Perot cavity. The fiber itself forms the cantilever: one end is simply supported in a SC ceramic ferrule and the 45-angled facet freely suspended. Therefore, the accelerometer is simply fabricated by inserting the ceramic ferrule into the sleeve. No extra alignment is required.

Thinner and longer cantilever is required to improve the sensitivity of the accelerometer. The length of the commercial SC sleeve is 11.4 mm, so the length of the fiber cantilever is controlled to be ~ 7 mm because

stable fixation between the sleeve and ferrule should be guaranteed. The diameter of the tail end of the cantilever beam is etched to be 57 um with hydrofluoric acid. The free end of the beam is kept unchanged with the help of positive photoresist. The length of the etched fiber beam is 3.5 mm. The resonant frequency of the fabricated accelerometer is 450 Hz. The sensor exhibits a flat frequency response in the range of 20-200 Hz with a high phase sensitivity of 16 dB re 1 rad/g. The minimal detectable acceleration is estimated to be 60 ug/Hz^1/2. The directional cross-sensitivity is measured to be 20dB.

10110-57, Session PWed

Phase demodulation of Fabry-Perot interferometer-based acoustic sensor utilizing tunable filter with two quadrature wavelengths

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A phase demodulation method for diaphragm-based short-cavity FPI based on two orthogonal wavelengths via a tunable optical filter is proposed in this paper. A broadband light is launched into the FPI sensor and two monochromatic beams with 3dB bandwidth of 0.2nm are selected out from the reflected light of the FPI sensor. A phase bias is induced between the two interferential signals via the wavelength difference of the two beams. The wavelength difference have a effect on the sensitivity of demodulated signal, which has been theoretically and experimentally demonstrated. The maximum sensitivity can be obtained when the phase bias is 0.5ϖ, corresponding to the wavelength difference of 1/4 FSR of the FPI spectrum. The acoustic wave induced phase variation can be demodulated through an optimized differential cross multiply (DCM) method. A normalization process is applied to the traditional differential cross multiply (DCM) method to eliminate the influence of ambient temperature and pressure fluctuation induced spectrum shift on output signal. This means that, once the wavelength difference is fixed, the wavelength variation of each individual beam will have little influence on the amplitude of demodulated signal. The FPI sensor head is formed by a 3?m-thick aluminum diaphragm, which has is SNR of more than 53dB. Through the proposed demodulation scheme, a large dynamic range and good linearity is acquired and Q-point drift problem of traditional FPI sensor can be solved. The demodulation scheme can be applied to the widely-used short-cavity FPI based acoustic sensors.

10110-58, Session PWed

A flexible fiber displacement sensor with tunable resolution and dynamic range based on a few-mode fiber loop

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In this article, we propose a fiber displacement sensor based on a few mode fiber loop sandwiched between two single mode fibers (SMF). The proposed sensor is flexible due to the tunable resolution and dynamic range. The FMF is coiled to a fiber loop by making a knot. The in-line MZI sensing structure is fixed on a two dimensional (2D) translation stages. By moving one stage while another stage is fixed, the displacement is applied on the sensing structure. The resolution of the translation stage is 10?m. The few mode fiber loop acts as the transducer for the displacement sensing. The displacement will change the radius of the few mode fiber loop, which leads to a wavelength shift of the interference pattern. When the fiber loop has different initial radius, the same displacement will cause a different curvature variation. So the sensitivity of the wavelength shift to the displacement is dependent on the initial radius. A smaller initial radius of the loop will lead to a larger sensitivity, higher resolution but smaller dynamic range, so it is proper for micro displacement sensing. On the contrary is the lager initial radius that is proper for sensing in a large dynamic range. By simply adjusting the initial radius of the transducer loop, different sensitivity and resolution can be reached. Experimental results show the sensitivities of 0.267nm/mm, 0.384nm/mm, 0.749nm/mm and 1.06nm/mm for initial loop radius of 1.9cm, 1.5cm, 1cm and 0.75cm, respectively.

10110-60, Session PWed

A spectroscopic method of determining color of petroleum products using CIELab color space with LED illumination

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Color is an important metric for determining the quality of petroleum products, as it is a characteristic readily observed by operators and end users and can also be indicative of the degree of refinement of a petroleum product. There are two primary color standards covering a wide range of petroleum color in industry; ASTM D 156 (Saybolt Color Scale) and ASTM D 1500 (ASTM Color Scale). For highly refined petroleum products the industry uses the Saybolt color scale, ranging from 30 at the clearest to -15 at the darkest. Fuels that are darker in color than -15 on the Saybolt scale are tested using the ASTM Color scale, which ranges from 1 at the clearest to 7 at the darkest. As fuels age (increased time from the point of refinement), their color darkens as a result of oxidizing olefins, such as ethylene and propylene. Traditionally, this color scale is measured using a series of photodiodes and optical filters with a blackbody light source. The spectroscopic method described in this paper incorporates a white LED designed for the purpose of maximizing color measurements. The spectra are processed using CIE 1931 color space, which is then converted into CIELab color space. Results using this method are accurate and repeatable.

10110-61, Session PWed

Spectral analysis of white-light interferometer fringes

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Introduction of computational imaging technologies such as compressive imaging and single-pixel architecture provides a great opportunity to enhance performance of optical measurement devices by replacing their imaging system (that usually consist of a CCD/CMOS camera) with more advanced and capable imaging technologies such as multi-spectral imaging systems which provide extra information such as spectral density in addition to intensity image. In this paper we show that in the case of a white light interferometer with a multi spectral imaging system, the spectral information can enhance the performance by relaxing the requirements of white light interferometer such as vertical scan and extracting more information from the surface of the object such as contamination.

White light interferometry is an established interferometric technique for surface metrology and inspection in precision metrology. A white light interferometer usually consists of a broadband (white light) source, an interferometric objective, a moving vertical arm, and a CCD/CMOS camera. Based on images of the CCD/CMOS camera in different location of vertical arm, an interferogram signal is generated for every pixel of the CCD/ CMOS camera. Locations of the maximum visibility of these signals are correspondent to the height of the object.

Susceptibility to surface contamination and requirement for mechanical vertical scan are some of the main issues in current white light

interferometers' designs. By utilizing spectral information, we have developed new algorithms for processing of white light interferometer fringes. Based on results from the simulation and experimental setup, we show that how these spectral analyses remove or immensely decrease the requirement for vertical scan in white light interferometry and how the extra spectral information could be used for detection of surface contamination.

10110-62, Session PWed

Micro-thermography and applications

Ki-Soo Chang, Dong Uk Kim, Chan-Bae Jeong, Geon-Hee Kim, Korea Basic Science Institute (Korea, Republic of)

More powerful and faster micro-electronic devices mean hotter devices, which can lead to a decrease in performance and lifetime. Thus, thermal analyses of micro-electronic devices, such as surface temperature profile measurements and localized heat generation detection under their operating conditions, have become an important factor in the development of semiconductor devices. Several thermal imaging and analysis techniques, such as scanning thermal microscopy, micro-Raman thermography, infrared micro-thermography, and thermoreflectance microscopy have been developed to investigate thermal properties in micro- and nano-scale devices.

In this presentation, we demonstrate quantitative micro-thermography, including infrared micro-thermography and thermoreflectance microscopy. Several applications of micro-thermography, such as quantitative measurement of the surface and sub-surface temperature distribution of semiconductor devices, hot spot detection for failure analysis of semiconductor integrated circuits, and detection of defects in optical materials, which act as laser-induced damage precursors, will be presented.

10110-63, Session PWed

An [phi]-OTDR and ROTDR hybrid system for distributed acoustic and temperature sensing

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We have proposed and experimentally demonstrated a distributed acoustic and temperature sensing system based on the hybrid of phase-sensitive optical time domain reflectometry (?-OTDR) and Raman optical time domain reflectometry (ROTDR). Single narrow line-width laser source of 1 kHz was utilized for optical probe pulse shaping with external modulation. The Rayleigh back scattering (RBS), Raman Stokes (RS) and anti-Stokes (RAS) generated by the probe pulse were separated by a high extinction ratio Raman filter. The RBS was received by a heterodyne detector while the RS and RAS components were received directly with avalanche photo detectors. With Hilbert Huang Transform (HHT), the phase change of the RBS interference signal was obtained with high accuracy, which could be used to fully rebuild the acoustic field applied on the sensing fiber. The ratio between RS and RAS was calculated and accumulated to obtain the temperature distribution. The experimental results have shown that the proposed hybrid system could realize fully distributed sensing along a 20km long standard single-mode fiber with 10m spatial resolution. Vibration event up to 1 kHz could be clearly distinguished with a remarkable signal-to-noise ratio (SNR). Multipoint temperature sensing could be obtained at the same time with an accuracy superior to 0.7?. The proposed method could be potentially used in the fields of seismic analysis, pipeline leakage detection and production flow monitoring, which extends the application realm of distributed optical fiber sensor (DOFS) technologies.

10110-64, Session PWed

Miniature and micro spectrometers market: who is going to catch the value?

Clémentine Bouyé, Benoît d'Humières, TEMATYS (France)

The market of miniature and micro spectrometers is evolving fast. The technology is getting ever smaller and cheaper while keeping high performances, as shows the latest products released by Hamamatsu (Japan), Ocean Optics (The Netherlands) and others. The market is attracting new players: spin-offs from major research institutes like Fraunhofer IPMS (Germany) or VTT (Finland) and large companies outside the classic spectroscopy market like Texas Instruments.

The goal of this involvement is to bring spectroscopy closer to the end-users and provide spectrometers able to operate on-field or in-line. Miniature and micro spectrometers are investigated for a wide variety of applications: chemistry, pharmaceutics, agro-food, agriculture, forensics, healthcare, consumer applications, … For now, they are well adopted in academic laboratories. Only one industrial application is well-established: the optical characterization of lasers, LEDS and displays. All other markets are more an accumulation of custom developments based on specifications provided by end-users.

The high potential of compact spectrometers is recognized but its emergence as a large volume market faces a major bottleneck. Each application implies specific processes and analyses and specific parameters to control, i.e. a specific interpretation of the raw spectra in order to provide information usable by non-photonic experts.

Who is going to pay for that adaptation effort? Are there ways for reducing the adaptation costs, by means of self-learning algorithms and/or flexible and easily adaptable sensors? In other words, who is going to catch the value?

In this article, we will wonder, what are the strengths and weaknesses of the different players - spectrometer manufacturers, algorithms developers or full-systems providers. We will also investigate the potential of each major industrial application market and provide market data.

10110-65, Session PWed

Automatic optical inspection of regular grid patterns with an inspection camera used below the Shannon-Nyquist criterion for optical resolution

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An Automatic Optical Inspection (AOI) system for optical inspection of imaging devices used in automotive industry using an inspecting optics of lower spatial resolution than the device under inspection is described. This system has is robust and with no moving parts. The cycle time is small. Its main advantage is that it is capable of detecting and quantify defects in regular patterns, working below the Shannon-Nyquist criterion for optical resolution, using a single low resolution image sensor. It is easily scalable, which is an important advantage in industrial applications, since the same inspecting sensor can be reused for increasingly higher spatial resolutions of the devices to be inspected.

The optical inspection is implemented with a notch multi-band Fourier filter, making the procedure especially fitted for regular patterns, like the ones that can be produced in image displays and Head Up Displays. The regular patterns are used in production line only, for inspection purposes. For image displays, functional defects are detected at the level of a sub-image element

unit. Functional defects are the ones impairing the function of the display, and are preferred in AOI to the direct geometric imaging, since these are the ones directly related with the end-user experience. The shift in emphasis from geometric imaging to functional imaging critical, since it is this that allows quantitative inspection, below Shannon-Nyquist. For HUDs, the functional detect detection addresses defects resulting from the combined effect of the image display and the image forming optics.

10110-66, Session PWed

Optimization of linear-logarithmic CMOS image sensor using a photogate and a cascode MOSFET for reducing pixel response variation

Myunghan Bae, Byoung-Soo Choi, Sang-Hwan Kim, Jimin Lee, Chang-Woo Oh, Jang-Kyoo Shin, Kyungpook National Univ. (Korea, Republic of)

Recently, CMOS image sensors (CISs) have become more and more complex because they require high-performances such as wide dynamic range, low-noise, high-speed operation, high resolution and so on. First of all, wide dynamic range (WDR) is the first requirement for high-performance CIS. Several techniques have been proposed to improve the dynamic range. Although logarithmic pixel can achieve wide dynamic range, it leads to a poor signal-to-noise ratio due to small output swings. Furthermore, the fixed pattern noise of logarithmic pixel is significantly greater compared with other CISs. In this paper, we propose an optimized linear-logarithmic pixel. Compared to a conventional 3-transistor active pixel sensor structure, the proposed linear-logarithmic pixel is using a photogate and a cascode MOSFET in addition. The photogate which is surrounding a photodiode carries out change of sensitivity in the linear response and thus increases the dynamic range. The logarithmic response is caused by a cascode MOSFET. Although the dynamic range of the pixel has been improved, output curves of each pixel were not uniform. In general, as the number of devices increases in the pixel, pixel response variation is more pronounced. Hence, we optimized the linear-logarithmic pixel structure to minimize the pixel response variation. We applied a hard reset method and an optimized cascode MOSFET to the proposed pixel for reducing pixel response variation. Unlike the conventional reset operation, a hard reset using a p-type MOSFET fixes the voltage of each pixel to the same voltage. This reduces non-uniformity of the response in the linear response. The optimized cascode MOSFET achieves less variation in the logarithmic response. We have verified that the optimized pixel shows more uniform response than the conventional pixel, by both simulation and experiment.

10110-67, Session PWed

Extraction of depth information for 3D imaging using pixel aperture technique

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The 3dimensional (3D) imaging is an important area which can be applied to face detection, gesture recognition, and 3D reconstruction. In this paper, extraction of depth information for 3D imaging using pixel aperture technique is presented. An active pixel sensor with in-pixel aperture has been developed for this purpose. In the conventional camera systems using a complementary metal-oxide-semiconductor (CMOS) image sensor, an aperture is located behind the camera lens. However, in our proposed camera system, the aperture implemented by metal layer of CMOS process is located on the White (W) pixel which means a pixel without any color filter on top of the pixel. 4 types of pixels including Red (R), Green (G), Blue (B), and White (W) pixels were used for pixel aperture technique.

The RGB pixels produce a defocused image with blur, while W pixels produce a focused image. The focused image is used as a reference image to extract the depth information for 3D imaging. This image can be compared with the defocused image from RGB pixels. Therefore, depth information can be extracted by comparing defocused image with focused image using the depth from defocus (DFD) method. Size of the pixel for 4-tr APS is 2.8 μm ? 2.8 μm and the pixel structure was designed and simulated based on 0.11 μm CMOS image sensor (CIS) process. Optical performances of the pixel aperture technique were evaluated using optical simulation with finite-difference time-domain (FDTD) method and electrical performances were evaluated using TCAD.

10110-28, Session 7

Investigation on fiber-optic strain-sensor based on microfiber MZI with temperature insensitivity

Seung Min Lee, Jong-Cheol Shin, Ju Il Hwang, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

Fiber optic strain sensors have been attractive because of their many advantages, such as electromagnetic immunity, ease installation into complex structures like aerospace, marine, or civil structures [1]. The Mach-Zehnder interferometric (MZI) strain sensor with high sensitivity is one of the most widely exploited sensing structure. Since the drawback of the conventional MZI, however, is high temperature-sensitivity resulting in the distortion of the measuring signal, it is necessary to suppress its temperature sensitivity for measurement of strain. To solve this problem, the photonic crystal fibers (PCFs)-based MZI strain sensor with temperature-insensitivity was investigated [2]. Since the core and the cladding of PCFs are composed of silica, the PCF-based MZI sensors have low temperature sensitivity. However, the PCF-based-MZI sensors have disadvantages of high insertion and coupling losses. The splicing point between the single-mode fiber (SMF) and the PCF must be fragile mechanically. Recently, there has been great interest in the microfiber MZI because of its low insertion loss, good stability, low cost, and robustness [3]. Microfibers with the strong evanescent field have been investigated in a variety of applications, such as microfiber Bragg grating [4], loop resonator [5], microfluidic channel [6] and microcoil resonator [7]. In this paper, a microfiber-based MZI for measurement of absolute strain is theoretically and experimentally investigated. When the diameter of the microfiber is ~7 ?m, the temperature sensitivity of the microfiber-MZI is dramatically reduced. We measure the strain sensitivity of the microfiber MZI, which is estimated to be 7.53?10-4 nm^-1· ??^-1 in the spatial frequency domain.

10110-29, Session 7

Design of a photonic integrated based optical interrogator

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Optical sensors based on Fiber Bragg Gratings (FBGs) are used in several applications and industries. In order for fiber optic sensors to compete with electrical sensors, several critical parameters of both the sensors and sensor interrogators need to be in place such as performance, cost, size, reliability relevant to the target application. Here we have developed a tunable laser based optical interrogator which delivers high performance (up to 8kHz and 120dB dynamic range) and precision (<100fm) by optimizing the laser calibration of a telecom tunable laser and incorporating optical periodic wavelength references (e.g. MZI) to correct and compensate for wavelength non-linearity and noise during operation. Scaling up optical sensing systems to deliver high level of performance over a large number of sensors is enabled by synchronizing multiple interrogators. Further improvements can be achieved by using photonic integrated circuit (PIC) technology which reduces the footprint, cost, and improves performance. There exists several PIC technology platforms (e.g. InP, Si, TriPlex) that could be used to develop different optical building blocks used in the interrogator. Such building blocks include the tunable laser, couplers, photodiodes, MZIs, etc. are available on the InP platform. Here we have demonstrated the operation of an interrogator using PIC technology to replace many of the discrete optical components. The design and chip manufacturing was carried out as part of an InP multi-project wafer (MPW) run under the EU PARADIGM project. A custom package supporting fiber arrays was designed and manufactured to demonstrate the PIC functionality in an optical interrogator.

10110-30, Session 7

Torsion sensing setup based on a Mach-Zehnder interferometer with photonics crystal fiber

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A torsion experimental sensing setup based on a Mach-Zehnder interferometer (MZI) with photonics crystal fiber is presented. Here, a Mach-Zehnder interferometer was fabricated by fusion splicing a segment of photonic crystal fiber (PCF) between two segments of a single-mode fiber (SMF). Moreover, the core and cladding were used as arms of the MZI, while the collapsed regions act as optical couplers. A spectral MZI fringe shifting is induced by applying torsion over the SMF-PCF-SMF. As a result a torsion sensitivity of 35.79 pm/º and a high visibility of 10 dB were achieved. It is important to point out than a higher visibility is a very important parameter for sensing physical parameter, since a higher visibility a more accurate measurement is achieved. Finally, it is shown that the sensing arrangement is compact and robust.

10110-31, Session 7

An all-digital low-cost and high-speed refractive index sensor based on optical fiber interferometry

Wenge Zhu, Jianan Tang, Lei Yuan, Hai Xiao, Clemson Univ. (United States)

Benefit from the advantages of small size, low weight and low noise, optical fiber has attracted a lot of interest for refractive index sensing. Fiber based interferometric interrogation is widely investigated, where the optical path difference changes with the refractive index. In spectrum domain, the fringes in interferogram shift with the refractive index. However, the sweep time of optical spectrum analyzer limits the sensing speed and increases the cost. As such, developing a low-cost, high speed refractive index sensor is of great interest and challenge.

In this paper, we proposed an all-digital refractive index sensor based on a series of Mach–Zehnder interferometers (MZI), which has incorporated intermodal interference between core mode and cladding mode. The N MZIs are fabricated by femtosecond laser machining, with their optical path difference arranged in the form of 2-times increments (i.e., OPDi = 2OPDi-1). When N MZIs are under test over a refractive index range respectively, the transmission signals exhibit sinusoidal waveforms with their free spectrum range (FSR) arranged in the form of 2-times decrements (i.e., 2FSRi = FSRi-1). After compared with the threshold, the sinusoid spectra are transformed to rectangular digital signals. In the view point of digital signals, the combination of these rectangular signals manifest N-bit Grey codes, which uniquely map to the 2N corresponding refractive index segments. As such, a refractive index meter is achieved with low cost, high speed, flexible range and resolution.

10110-32, Session 7

Gain-assisted broadband ring cavity enhanced spectroscopy

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Incoherent broadband cavity enhanced spectroscopy (CES) can significantly increase the effective path length of light-matter interaction to detect weak absorption lines over broad spectral rangeand to detect gases in confined environments. Broadband cavity enhancement can be based on decay time or intensity drop. Decay time measurement is based on using tunable laser source that is expensive and suffers from long scan time. Intensity dependent measurement is usually reported based on broadband source using Fabry-Perot cavity, enabling short measurement time but suffers from the alignment tolerance of the cavity and the cavity insertion loss. In this work we solve these challenges by using alignment-free ring cavity made of optical fiber loop and directional coupler and having a gain medium pumped below the lasing threshold to improve the finesse and reduce the insertion loss. Acetylene (C2H2) gas absorption is measured around 1535 nm wavelength and the gain medium is semiconductor optical amplifier (SOA). The system is analyzed for different ring resonator forward coupling coefficient and loses, corresponding to the 3-cm long gas cell insertion loss and fiber connector losses. The experimental results are obtained for coupler ratio of 90/10 and fiber length of 4 m. The broadband source is the amplified spontaneous emission of another SOA and the output is measured using a 70-pm resolution optical spectrum analyzer. The absorption depth and the effective interaction length are improved about order of magnitude compared to the direct absorption of the gas cell. The presented technique provided an engineering method to improve the finesse and, consequently, the effective length in CES while relaxing the technological constraints on the high reflectivity mirrors and free-space cavity alignment.

10110-33, Session 8

Waveguide-enhanced Raman scattering for chemical sensing *(Invited Paper)*

Scott A. Holmstrom, The Univ. of Tulsa (United States); Todd H. Stievater, Dmitry A. Kozak, R. Andrew McGill, U.S. Naval Research Lab. (United States)

We will review the state of the art for on-chip, Raman-based sensing using waveguides including our recent work with sorbent-coated waveguides for trace gas sensing showing parts-per-billion limits of detection. We will show that signal enhancements due to scattering that takes place in the evanescent field coupled with a thin hypersorbent polymer coating can yield Raman efficiencies which are nine orders of magnitude larger than traditional micro-Raman techniques. We will also discuss challenges with gas component discrimination and in moving toward a fully integrated photonic circuit architecture for handheld Raman-based trace gas sensors.

10110-34, Session 8

A quantitative comparison of dispersion- and absorption- spectroscopic gas sensing

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We present a quantitative comparison between novel laser dispersion spectroscopy and established absorption spectroscopy schemes for gas phase analysis in the Mid-IR spectral range. Dispersion spectroscopy

senses changes in refractive index caused by molecular resonances via measurements of phase. Hence, it is insensitive to intensity fluctuations and differs from absorption measurements in multiple aspects.

In the comparative discussion, absorption and dispersion spectroscopy are exemplified by two techniques, wavelength modulation spectroscopy [1] and heterodyne phase sensitive dispersion spectroscopy [2]. The former employs modulation of the laser frequency to yield amplitude spectra. The resulting amplitude, as for any absorption based scheme, needs to be normalized to the laser intensity. Normalization, however, requires one to constantly detect the laser power and can limit the method's accuracy through errors and noise of the reference. In heterodyne phase sensitive dispersion spectroscopy this problem is overcome. Intensity modulation of the laser yields spectra of amplitude and phase, of which both are sensitive measures of the sample concentration. The phase of the signal linearly depends on the concentration of the absorbing gas and is independent from the laser power. This greatly improves the robustness of the method and avoids the necessity for calibration.

Based on analytical modeling of dispersion - and absorption spectroscopy we compare the methods' sensitivity and robustness towards different sources of noise and errors. We combine this analysis with practical experience and experimental results from the laboratory to give a comprehensive overview of potentials and limitations.

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10110-35, Session 8

Performance of ALD MCPs with optimized bias angles

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We present the results of characterization tests of the latest generation of borosilicate microchannel plates (MCPs) functionalized by Atomic Layer Deposition (ALD) of resistive and secondary emissive layers. These MCPs were produced with a higher bias angle (13 degrees) than previously to optimize quantum efficiency, and were functionalized with MgO for better expected gain performance with refined manufacturing techniques. We measure gain characteristics, pulse amplitude distributions, quantum efficiency, and lifetime performance for a range of extracted charge. We also present trade studies for integration into detectors in instruments for application in astrophysical and planetary sciences.

10110-36, Session 8

Using quantum-dots to enable deep-UV sensitivity with standard silicon-based imaging detectors

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There is ongoing interest in extending the detection range for silicon based CMOS and CCD arrays into the deep UV. One commercially used approach is to coat such devices with an organic phosphor called Lumogen. This material fluoresces at visible wavelengths under UV illumination and some fraction of this emitted light is then captured by the detector. Lumogen, however, has several known issues including limitations to its use in vacuum and in radiation harsh environments. Quantum Dots (QD) offers a more robust alternative to Lumogen. The fluorescence wavelength of QDs is tunable and they can be fabricated so that the emitted light is better matched to the peak sensor quantum efficiency. A method utilizing aerosol jet printing is being investigated at RIT to enable uniform coating of sensor arrays with layers of QDs . Such coatings also improve the robustness of silicon arrays in some applications. For example current generation lithography for integrated circuit production is exposed with 193nm light with future generations moving to even shorter wavelengths down to 13.5nm. Silicon based sensors' performance degrades under exposure to such deep UV radiation. The QD coating will not degrade over time and has very high absorption efficiency in this spectral reason thereby protecting the underlying silicon

10110-37, Session 9

Snapshot Stokes polarimeters based on a single biaxial crystal

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Snapshot polarimeters are used to measure light polarization variations in dynamic processes. A type of snapshot polarimeters are those based on the conical refraction (CR) phenomenon, occurring in biaxial crystals (BCs). CR phenomenon is of interest in polarimetry because under certain conditions, it provides the linear content of an input beam from a single intensity image. Compared with existing snapshot polarimeters, BCs based polarimeters are quite repeatable instruments. Moreover, unlike most polarimeters, which require time-sequential measures to decrease noise, BCs based polarimeters do that instantaneously because redundancy data is spatially obtained from intensity images.

So far, optical arrangements proposed for BC based polarimeters requires of two optical arms, each one including a BC and a CCD camera. Those elements are duplicated because a single BC only provides linear content of input beams, so an extra arm including a linear retarder is required for complete polarimetric metrology. This situation increases the set-up complexity as well as the polarimeter final cost.

We propose two different schemes for the implementation of an inline BC polarimeter, both of them only requiring one BC and a single CCD camera. The first scheme is restricted to linear metrology and we provide its interest to be applied under low-intensity conditions. The second architecture is suitable for complete polarimetry, this situation being achieved by including an optical module properly splitting and steering the input light. Both schemes are optimized and experimentally implemented. The BC polarimeters were tested by measuring different known input polarizations and we obtained excellent results.

10110-38, Session 9

Hyperspectral imaging using a commercial light-field camera

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Hyperspectral imaging allows the collection of both spectral and spatial information. This modality is naturally fitted for object and material identification or detection processes, and has encountered a large success in the agriculture and food industries to name a few.

In snapshot spectral imaging, the 3D cube of images is taken in one shot, with the advantage that dynamic scenes can be analyzed. The simplest way to make a hyperspectral camera is to put an array of wavelength filters on the detector and then integrate this detector with standard camera objectives. The technical challenge is to make arrays of N wavelength filters and repeat this sequence up to 100'000 times across the detector array, where each individual filter is matched to the pixel size and can be as small as a few microns.

In this work, we generate the same effect with just one N wavelength filter array which is then multiplied and imaged optically onto the detector to achieve the same effective filter array. This was first outlined by Levoy and Hoystmeyer using microlens arrays in a light field camera (plenoptics 1.0). Instead of building our own light field camera we used an existing commercial camera, Lytro™ and used it as the engine for our telecentric hyperspectral camera. In addition, the tools to extract and rebuild the raw data from the Lytro™ camera were developed.

We demonstrate reconstructed hyperspectral images with 9 spectral channels and show how this can be increased to achieve 81 spectral channels in a single snapshot.

10110-39, Session 9

Fast and compact internal scanning CMOS-based hyperspectral camera

Julien Pichette, Wouter Charle, Andy Lambrechts, IMEC (Belgium)

Imec has developed a process for the monolithic integration of optical filters on top of CMOS image sensors, leading to compact, cost-efficient and faster hyperspectral cameras. Imec developed both mosaic (4x4 VIS 470-620 nm range and 5x5 VNIR 600-1000 nm) and linescan sensors (LS100 100+ bands 600-1000 nm and LS150 150+ bands from 475-925 nm) based on CMOSIS CMV2000 image sensor.

Linescan cameras are typically used in remote sensing or for conveyor belt applications, wherein the object moves in relation to the image sensor. They offer both high spectral and spatial resolutions: 100-150+ spectral bands with 2048 columns. Translation of the target is not always possible (or practical) for large objects or in many medical applications (e.g. brain and wound imaging). Snapshot mosaic sensors can offer a good alternative to linescan with their real-time capabilities, but their lower resolution can be a problem in some applications.

To circumvent these issues, we introduce a novel camera exploiting internal movement of a linescan sensor enabling fast and convenient acquisition of hyperspectral cubes of static targets. We present results with our high-resolution hyperspectral cubes (2048x3072x150) which can be acquired quickly (@ up to 180 frames per second) without perspective deformation using our LS150 150+ bands from 475-925 nm. Noise can be greatly reduced by implementing digital time delay integration. Spectrally corrected data of reference targets (colored Spectralon tiled) and outdoor scenes will be presented to exhibit the capabilities of the camera system.

10110-40, Session 9

Comparison of an all-in-fiber low-coherence interferometer with a free-space interferometer for surface profilometry

Christopher Taudt, Tobias Baselt, Westsächsische Hochschule Zwickau (Germany) and Fraunhofer Institut für Werkstoff- und Strahltechnik IWS (Germany); Bryan L. Nelsen, Westsächsische Hochschule Zwickau (Germany); Heiko Assmann, Infineon Dresden GmbH (Germany); Andreas Greiner, Infineon Technologies Dresden (Germany); Edmund Koch, TU Dresden (Germany); Peter Hartmann, Westsächsische Hochschule Zwickau (Germany)

Modern manufacturing technologies for semiconductor technologies, MEMS and thin-film processing set high demands regarding quality, precision and reliability. Appropriate surface topography measurement technologies should therefore deliver nm-accuracy in the axial dimension while enabling a rather larger, μm-sized, measurement range along the sample's surface.

This work shows the characterization of an all-in-fiber low-coherence interferometer for the purpose of fast and robust surface topography measurements. Besides the piezo-based fiber stretcher, the key component of the interferometer is an element with known dispersion. This dispersive element delivers a controlled phase variation in relation to the surface height variation which can be detected in the spectral domain. Due to the known dispersion characteristics, it becomes possible to calculate the surface profile with nm-precision from the phase-varied spectral data.

A laboratory setup equipped with a broadband supercontinuum light source (380 - 1100 nm) was established. Initial experiments were carried out on a silicon-based standard with height steps of 100 nm. The analyzed data showed that a height resolution of 10 nm was possible. Additionally, the setup is characterized in terms of its stability regarding temperature and vibration as well as the possible measurement speed. It could be shown, that measurements in the kHz-range were possible. All obtained results were compared with appropriate measurements in a free-space setup. It was found that the all-in-fiber approach performs significantly better in all aspects. A discussion of the implications of these findings regarding the usability of the metrology approach in industrial use cases concludes the work.

10110-41, Session 9

Development of an integrated sub-picometric SWIFTS-based wavelength meter

Céline Duchemin, Fabrice Thomas, Bruno Martin, Renaud Puget, Eric Morino, Christophe Bonneville, Thierry Gonthiez, Nicolas Valognes, RESOLUTION Spectra Systems (France)

SWIFTS technology has been known for over five years to offer compact and high-resolution laser spectrum analyzers. The increase of wavelength monitoring demand with even better accuracy and resolution pushed the development of a wavelength meter based on SWIFTS technology, named LW-10.

As a reminder, SWIFTS technology consists in a waveguide in which a stationary wave is created, sampled and read out by a linear image sensor array. Due to its inherent properties (non-uniform subsampling) and aliasing signal (as presented in Shannon-Nyquist criterion), the system offers short spectral window width thus needs an a priori on the working wavelength and thermal monitoring.

Although SWIFTS-based devices are barely sensitive to atmospheric pressure, temperature control is a key factor to master both high accuracy and wavelength meter resolution. Temperature control went from passive (temperature probing only) to active control (Peltier thermoelectric cooler) with milli-degree accuracy. The software part consists in dropping the Fourier-like transform, for a least-squares method directly on the interference pattern. Moreover, the consideration of the system's chromatic behavior provides a "signature" for automated wavelength detection and discrimination. New advanced calibration methods were also set-up to meet new requirements.

This SWIFTS-based new device LW-10, shows outstanding results in terms of absolute accuracy, wavelength-meter resolution as well as calibration robustness within a compact device, compared to other existing technologies. On the 630-1100 nm range, the final device configuration allows pulsed or CW lasers monitoring with 20 MHz resolution and 200 MHz absolute accuracy. Non-exhaustive applications include tunable laser control and frequency locking experiments.

10110-42, Session 10

High-resolution Raman spectroscopy with broadband light sources *(Invited Paper)*

Vladislav V. Yakovlev, Texas A&M Univ. (United States)

Raman spectroscopy is traditionally based on the use of narrow-band light sources for excitation. Substantial efforts are devoted to minimize the line-width of the incident radiation to obtain high-resolution Raman spectra. We proposed and experimentally validate a novel approach, in which a broadband laser or LED is used. The light is spectrally dispersed, focused on a surface of sample and a collected Raman signal is re-imaged on the entrance slit of an imaging spectrometer. Using a simple retrieval algorithm, high resolution Raman spectra are extracted with exceptional signal-to-noise ratio and relative insensitivity to a fluorescence background.

10110-43, Session 10

Quantum-cascade-laser-based heterodyne phase-sensitive dispersion spectroscopy in the mid-IR range: capabilities and limitations

Pedro Martín-Mateos, Univ. Carlos III de Madrid (Spain); Jakob Hayden, Institut für Chemische Technologien und Analytik, Technische Univ. Wien (Austria); Pablo Acedo, Univ. Carlos III de Madrid (Spain); Bernhard Lendl, Institut für Chemische Technologien und Analytik, Technische Univ. Wien (Austria)

In this paper we present the first implementation of Heterodyne Phase Sensitive Dispersion Spectroscopy (HPSDS) in the Mid-IR range for gas sensing based on a CW operated Distributed Feedback Quantum Cascade Laser (DFB-QCL). HPSDS is based on the detection of the different phase velocities, caused by molecular resonances, in the modes of a three tone optical signal (created by sinusoidally modulating the current of the QCL). These different velocities induce phase shifts between the three laser lines that are directly dependent on the concentration of gas. Therefore, gas concentration can be retrieved from the measurement of the phase of the beat note that is generated when the optical signal impinges on a photodetector.

Compared to absorption spectroscopy HPSDS is characterized by the following, highly interesting, features: It offers an output that is linearly dependent on the gas concentration, it is inherently normalization-free and baseline-free and it is also immune to power fluctuations. Different concentrations of CO in nitrogen in the low and sub ppm range were measured at various pressures in a 100 m Herriot absorption cell for assessing the performance of the method at first. The set-up is finally employed to study with high-resolution the concentration of carbon monoxide in ambient air.

10110-44, Session 10

Miniature Raman spectroscopy utilizing stabilized diode lasers and 2D CMOS detector arrays

Bryan Auz, Ty Olmstead, Matthew Comstock, John Rodriguez, Ocean Optics, Inc. (United States)

Raman spectroscopy has been around since the 1920's when it was first observed by C.V. Raman. However, the technique did not become a prominent spectroscopic analysis tool until the 1960's with the advent of the laser. With laser light readily available the Raman effect was brought to the forefront of analytical techniques including characterizing chemical composition, compound identification, counterfeit substance verification, particle size analysis, and many more. Since Raman spectroscopy entered the mainstream much of the focus has been on miniaturizing the components of these systems such that they can make their way out of laboratories and into the field. This paper focuses on the use of Peltier effect temperature stabilized and Bragg grating wavelength stabilized diode lasers in conjunction with two dimensional CMOS detector arrays to create a miniature Raman spectrophotometer. As well as the laser and detector system components will include optical elements, opto-mechanics, and software. This review will include details of the component selection process, system design considerations, and system setup. When designing any optical system compromises must be made in certain areas of system performance to gain an advantage in others. Component selection and system design will explain the tradeoffs that must be dealt with when specifying a Raman system and how the process for making those decisions is affected by the miniature system size. System setup and alignment requirements will be followed by results from the system at 638nm and 785nm excitations. These results will be presented in the form of Raman spectra taken from commonly available substances including sulfur, cyclohexane, toluene, and polystyrene.

10111-1, Session 1

Creating revolutionary imaging technologies *(Keynote Presentation)*

Jay S. Lewis, Defense Advanced Research Projects Agency (United States)

This paper will review several ongoing or emerging DARPA programs. This will include the Wafer Scale Infrared Detectors (WIRED) program, which aims to develop detector technologies that can be fabricated directly on wafer-scale integrated circuits. We will also discuss the Reconfigurable Imaging (ReImagine) program, which seeks to access more information in the scene than is currently possible in a single camera. Finally, we will update progress in the Pixel Network for Dynamic Visualization (PIXNET) program, which seeks to provide real-time multi-band imagery in a small, wearable form factor.

10111-2, Session 1

Ultra-low detection limits and selectivity with organic bio-electronic sensors *(Keynote Presentation)*

Luisa Torsi, Eleonora Macchia, Kyriaki Manoli, Gerardo Palazzo, Univ. degli Studi di Bari Aldo Moro (Italy); Gianluca Lattanzi, Univ. degli Studi di Trento (Italy)

Point-of-care (POC) platforms are integrated diagnostic systems employed for the detection of clinically relevant biomarkers in biological fluids such as blood, urine and saliva. These devices offer the advantage to provide rapid results directly where the information is needed (e.g. patient's home, doctor's office or emergency room), thus facilitating an earlier diagnosis and a prompt patient's treatment. Various technologies have been proposed for the realization of POC biosensors including label-free techniques based on optical, mechanical and electrochemical transducers. However, reliable, quantitative and ultrasensitive devices have been not yet commercialized. Electronic biosensors based on organic thin-film transistors (OTFTs) are a promising choice for the development of the next generation of POC devices. These biosensors can be combined with integratedelectrical circuits, microfluidic systems and wireless technologies. Furthermore, they offer high sensitivity, biocompatibility and possibility to produce all-printed low-cost biosensors in flexible and disposable formats.Among them, electrolyte-gated (EG)-OTFTs have been identified as ideal candidates for biosensors development as they operate at low voltages directly in aqueous buffer solutions. Using these configurations ultrasensitive label-free immunosensors for the detection of C-reactive protein (CRP), a specific biomarker of inflammatory and infection diseases, at the femtomolar concentration level have been developed. The devices are also able to perform chiral differential detection of odorant molecules. The specific features of the proposed EGOTFT biosensors as well as their analytical performances will be discussed.

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10111-123, Session 1

A recent review of mid-wavelength infrared type-II superlattices: carrier localization, device performance, and radiation tolerance *(Keynote Presentation)*

Elizabeth H. Steenbergen, Charles J. Reyner, Gamini Ariyawansa, Joshua M. Duran, John E. Scheihing, Christian P. Morath, Geoffrey D. Jenkins, Vincent M. Cowan, Air Force Research Lab. (United States)

The last two decades have seen tremendous progress in the design and performance of mid-wavelength infrared (MWIR) type-II superlattices (T2SL) for detectors. The materials of focus have evolved from the initial InAs/(In)GaSb T2SL to include InAs/InAsSb T2SLs and most recently InGaAs/InAsSb SLs, with each materials system offering particular advantages and disadvantages. As the material quality of the InAs/(In)GaSb SLs increased to the point of being viable for devices, the problem of short minority carrier lifetimes was exposed. Then InAs/InAsSb SLs were found to have longer minority carrier lifetimes at the cost of lower absorption coefficients due to smaller band offsets than those of the InAs/(In)GaSb SLs. To address the lower absorption coefficient of InAs/InAsSb SLs, the InGaAs/InAsSb SLs have been designed and demonstrated a 30-35% increase in the absorption coefficient as compared to the reference InAs/InAsSb SL design. Part of the reason for the longer minority carrier lifetime in InAs/InAsSb SLs has been found to be due to carrier localization due to group-V As/Sb interface intermixing. For devices operating above the delocalization temperature, it is expected that the effects of carrier localization will be minimal. However, if the operating temperature is within the localization regime, the collection of photogenerated carriers may be impeded by localization and may result in a lower detector quantum efficiency. Radiation tolerance studies give insight into device degradation mechanisms in addition to suitability for space environments. Comparisons between the different SL materials and device characteristics will be presented.

10111-5, Session 2

Monitoring of short-lived climate pollutants by laser absorption spectroscopy *(Invited Paper)*

Gaoxuan Wang, Univ. du Littoral Côte d'Opale (France); Dong Chen, Hefei Univ. of Technology (China); Fengjiao Shen, Hongming Yi, Univ. du Littoral Côte d'Opale (France); Rabih Maamary, Patrick Augustin, Marc Fourmentin, Dorothée Dewaele, Fabrice Cazier, Université du Littoral Côte d'Opale (France); Patrice Hubert, Alexandre Deguine, Denis Petitprez, Univ. des Sciences et Technologies de Lille (France); Eric Fertein, Univ. du Littoral Côte d'Opale (France); Markus W. Sigrist, ETH Zürich (Switzerland); Weidong Chen, Univ. du Littoral Côte d'Opale (France)

Because of its long lifetime (~130 years) in the atmosphere, long-lasting CO2 will remain the primary driver of long-term temperature rise even if new CO2 emissions dropped to zero. A "fast-action" climate mitigation strategies is hence strongly needed to provide more sizeable short-term benefits than CO2 reductions by reducing emission of short-lived climate pollutants (SLCPs), having atmospheric lifetimes of less than 20 years. CH4, one of the most important SLCPs with an atmospheric lifetime of about 12

years, is considered as the second most powerful climate-forcing agent in the atmosphere after CO2. Black carbon (BC), with an atmospheric lifetime of about one week, is the second most important SLCPs after CH4. BC has been also identified as the most harmful air pollutant in terms of its adverse impacts on human health. Monitoring of climatically and environmentally active SLCPs is important not only for policy-based reporting, but also for basic process-based understanding of climate related processes in the atmosphere.

In this talk, we will overview our recent progress in the developments and applications of laser-based optical instruments for the measurements of environmental and livestock emitted CH4, as well as the measurement of BC absorption. The experimental detail, the preliminary measurement results, the corresponding data processing and analysis will be presented.

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10111-6, Session 2

QCL-based trace gas analyzer for industrial and healthcare applications *(Invited Paper)*

Akira Maekawa, Yasutomo Shiomi, Miyuki Uchida, Tsutomu Kakuno, Toshiba Corp. (Japan)

Trace gas analyzers using Quantum Cascade Laser was developed for industrial and healthcare applications.?

For healthcare applications, we develop isotopic ratio analyzer of breath CO2 for the detection of helicobacter pylori infection. Any other analyzers are also reported.

10111-7, Session 2

Single-tube on beam quartz-enhanced photoacoustic spectrophones exploiting a custom quartz tuning fork operating in the overtone mode

Marilena Giglio, Angelo Sampaolo, Univ. degli Studi di Bari Aldo Moro (Italy); Pietro Patimisco, Rice Univ. (United States); Huadan Zheng, Hongpeng Wu, Lei Dong, Shanxi Univ. (China); Frank K. Tittel, Rice Univ. (United States); Vincenzo Spagnolo, Politecnico di Bari (Italy)

Quartz-enhanced photoacoustic spectroscopy (QEPAS) is a well-established laser-based technique for gas sensing. Utilizing a quartz-tuning fork (QTF) to transduce the sound wave produced by an absorbing gas into an electrical signal, QEPAS offers compactness, high detection sensitivity and selectivity. QEPAS sensitivity can be further enhanced by means of acoustic amplification provided by two micro-resonator tubes and the QTF positioned between them. Recently, realization of custom-made QTFs opened the way for two novel approaches to increase the sensing performance of a QEPAS spectrophone. First, by designing QTFs with larger prongs has made it possible to accommodate between them a single-tube resonator, with a pair of slits realized where the acoustic pressure antinode is located. With this approach, the size of the QEPAS spectrophone was reduced with respect to a dual-tube configuration. Secondly, QTFs can be properly designed to enhance the first overtone mode providing higher quality factors with respect to the fundamental mode, thereby leading to increased QEPAS detection sensitivity.

In this work, we combined these two approaches and investigated the sensing performance of a single-tube on-beam QEPAS spectrophone exploiting custom QTFs operating in the overtone mode. We analyzed in detail how the geometry of the resonator tube influences the sensing performance of the QEPAS spectrophone. An additional improvement in QEPAS sensitivity can be obtained by using a novel QEPAS spectrophone composed of two acoustic resonators operating at the two antinodes of the overtone mode and employing a double-pass beam configuration.

10111-8, Session 2

CW DFB-QCL- and EC-QCL-based sensor for simultaneous NO and NO2 measurements via frequency modulation multiplexing using multi-pass absorption spectroscopy *(Invited Paper)*

Yajun Yu, Rice Univ. (United States) and Wuhan Univ. (China); Nancy P. Sanchez, Minhan Lou, Chuantao Zheng, Hongpeng Wu, Rice Univ. (United States); Aleksander K. G?uszek, Arkadiusz J. Hudzikowski, Rice University (United States); Robert J. Griffin, Frank K. Tittel, Rice Univ. (United States)

Nitrogen oxides (NOx), including nitric oxide (NO) and nitrogen dioxide (NO2), play important roles in determining the photochemistry of the ambient atmosphere, controlling the production of tropospheric ozone, affecting the concentration levels of the hydroxyl radical, and forming acid precipitation. In order to enable fast-response NOx detection, we developed a sensor system capable of simultaneous measurements of NO and NO2 by using a commercial 76-m astigmatic multi-pass gas cell (MPGC). A continuous wave (CW) distributed-feedback (DFB) quantum cascade laser (QCL) and a CW external-cavity (EC) QCL were employed for targeting a NO absorption doublet at 1900.075 cm-1 and a NO2 transition at 1630.33 cm-1, respectively. Both laser beams were combined and transmitted through the MPGC in an identical optical path and subsequently detected by a single mid-infrared detector. A frequency modulation multiplexing scheme was implemented by modulating the DFB-QCL and EC-QCL at different frequencies and demodulating the detector signal with two Labview software based lock-in amplifiers to extract the corresponding second-harmonic (2f) components. Continuous monitoring of NO and NO¬2 concentration levels was achieved by locking the laser frequencies to the selected absorption lines utilizing a reference cell filled with high concentrations of NO and NO2. The experimental results indicate minor performance degradation associated with frequency modulation multiplexing and no cross talk between the two multiplexed detection channels. The performance of the reported sensor system was evaluated for real time, sensitive and precise detection of NO and NO2 simultaneously.

10111-9, Session 2

Pure amplitude and wavelength modulation spectroscopy for detection of N2O using a three-section quantum cascade laser *(Invited Paper)*

Pietro Patimisco, Angelo Sampaolo, Univ. degli Studi di Bari Aldo Moro (Italy); Yves Bidaux, Alfredo Bismuto, Alpes Lasers SA (Switzerland); Marshall Scott, James Y. Jiang, Thorlabs, Inc. (United States); Frank K. Tittel, Rice Univ. (United States); Vincenzo Spagnolo, Politecnico di Bari (Italy)

The combination of single-mode emission and mode-hop free tunability makes quantum cascade lasers (QCLs) extremely suitable for sensitive and selective trace-gas detection. High detection sensitivities can be achieved by implementing a wavelength modulation (WM) technique in the kHz-frequency range, which reduces the 1/f-noise originating mainly from laser intensity fluctuations and mechanical instabilities. WM operation is typically obtained by modulating the QCL current, but this produces also modulation of the emitted output power. As a result, the acquired Lorentzian gas-

absorption profile exhibits a second-derivative lineshape, deformed by a residual intensity modulation (RAM) contribution.

In this work, we employed a novel QCL source allowing modulation of the laser intensity and frequency independently of each other. The QCL structure is composed of three electrically independent sections: the gain, the Phase (PS) and the Master Oscillator (MO) section. The QCL was employed in a quartz-enhanced photoacoustic spectroscopy (QEPAS) sensor for the acquisition of a N2O absorption line. When the PS current is modulated, the optical power is also modulated, while the emission wavelength remains constant. With this condition, a pure amplitude modulation configuration is reached. By adding a voltage signal to the MO section QEPAS background-free Lorentzian line-shape spectra were obtained for the targeted NO2 absorption line. When the MO current is modulated, the PS current can be adjusted in order to maintain constant the optical power during modulation. In this manner, a pure wavelength modulation, without any RAM contribution is obtained and the QEPAS spectra show a second-derivate Lorentzian function lineshape.

10111-10, Session 3

Hyperspectral imaging for standoff trace detection of explosives using quantum cascade lasers *(Invited Paper)*

Frank Fuchs, Stefan Hugger, Jan-Philip Jarvis, Marko Härtelt, Quankui K. Yang, Marcel Rattunde, Ralf Ostendorf, Christian Schilling, Rachid Driad, Rolf Aidam, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

Reliable standoff detection of traces of explosives is still a challenging task. Imaging MIR backscattering spectroscopy has been shown to be a promising technique for non-contact detection of traces of explosives on various surfaces. This technique, which is eye-safe, relies on active imaging with MIR laser illumination at various wavelengths. Recording the backscattered light with a MIR camera at each illumination wavelength, the MIR backscattering spectrum can be extracted from the three-dimensional data set recorded for each point within the laser illuminated area. Applying appropriate image analysis algorithms to this hyper-spectral data set, chemically sensitive and selective images of the surface of almost any object can be generated. This way, residues of explosives can be clearly identified on the basis of characteristic finger print backscattering spectra and separated from the corresponding spectra of the underlying material. To achieve a high selectivity, a large spectral coverage is a key requirement. Using a MIR EC-QCL with a tuning range from 7.5 μm to 9.5 μm, different explosives such as TNT, PETN and RDX residing on different background materials, such as painted metal sheets, cloth and polyamide, could be clearly detected and identified. For short stand-off detection distances (<3 m), residues of explosives at an amount of just a few 10 μg, i .e. traces corresponding to a single fingerprint, could be detected. For larger concentration of explosives, stand-off detection over distances of up to 20 m has already been demonstrated.

During the European FP7 projects EMPHASIS and HYPERION several field tests were performed at the test site of FOI in Sweden. During these tests realistic scenarios were established comprising test detonations of IEDs. We could demonstrate the potential of QCL-based imaging backscattering spectroscopy for the detection of trace amounts of hazardous substances in such scenarios.

10111-11, Session 3

Stabilizing infrared quantum cascade laser beams for standoff detection applications

Christopher Breshike, Christopher A. Kendziora, Robert Furstenberg, Viet K. Nguyen, R. Andrew McGill, U.S. Naval Research Lab. (United States)

We are developing a technology for standoff detection of chemicals on surfaces based on active broadband infrared imaging spectroscopy. This approach leverages one or more micro-fabricated IR quantum cascade lasers, tuned to strong absorption bands in the analytes and directed to illuminate an area on a surface of interest. An IR focal plane array is used to image the surface response upon laser illumination. The broadband IR signal is processed as a hyperspectral image cube comprised of spatial, spectral and temporal dimensions as vectors within a detection algorithm. These applications place stringent stability requirements on the wavelength, power, pulse width and spatial beam profile that pose a challenge for broadly tunable IR QCL. We demonstrate methods to mitigate these challenges including infrared fibers and active feedback stabilization. We have previously demonstrated standoff trace detection at several meters indoors and in field tests, while operating the lasers below the eye-safe intensity limit (100 mW/cm2). Sensitivity to explosive traces as small as a single grain (~1 ng) has been demonstrated. Analytes tested include RDX, TNT, ammonium nitrate and perchlorates. Relevant substrates include metal, plastics, glass and painted car panels.

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10111-12, Session 3

Low power consumption quartz-enhanced photoacoustic gas sensor employing a quantum cascade laser in pulsed operation

Angelo Sampaolo, Univ. degli Studi di Bari Aldo Moro (Italy); Pietro Patimisco, Aleksander K. Gluszek, Arkadiusz J. Hudzikowski, Rice Univ. (United States); Marilena Giglio, Univ. degli Studi di Bari Aldo Moro (Italy); Huadan Zheng, Rice University (United States); Frank K. Tittel, Rice Univ. (United States); Vincenzo Spagnolo, Politecnico di Bari (Italy)

Gas sensing techniques based on laser absorption spectroscopy are excellent candidates for real-world applications requiring fast and in-situ measurements. When operating at atmospheric pressure, trace gas sensors based on optical techniques share two main sources of power consumption: a laser source that typically requires an air- or water-cooled system for temperature stabilization and a cooled infrared photodetector. Quartz-enhanced photo-acoustic spectroscopy (QEPAS) is the only laser-based technique that does not require an optical detector, since the quartz tuning fork (QTF) itself acts as an uncooled, wavelength insensitive detector with negligible power consumption. Therefore, QEPAS is an ideal technique for the realization of trace gas sensors with low-power consumption. The power consumption of a QEPAS gas sensor system could be reduced even further if operating with pulsed laser sources, thus avoiding the use of cooling systems.

We report here an experimental investigation of the performance of a low-power consumption QEPAS gas sensor employing a quantum cascade laser (QCL) operating in a pulsed mode. The QEPAS sensor targets a carbon monoxide absorption line at 2169.2 cm-1. We analyzed the QEPAS signal characteristics as function of the QCL injected current, pulse width and frequency. Duty-cycles as low as 10% were reached, lowering the laser power consumption down to 0.34 W. Two QTFs with different prong spacings (300 ?m and 700 ?m) and resonance frequencies (32.7 kHz and 4.2 kHz) were employed to study the influence of the operating frequency and photo-thermal effects arising from a portion of the QCL output illuminating the QTF surface.

10111-13, Session 3

Nanospectroscopy of single purple membranes by mid-IR resonantly-enhanced mechanical photoexpansion

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In this work we apply the recent mid-IR resonantly-enhanced mechanical photoexpansion technique to perform vibrational imaging and nanospectroscopy of single purple membranes, i.e. cell membranes densely filled with bacteriorhodopsin (bR), a protein acting as a proton pump across the cell membrane of Halobacteria. Our experiments are performed using the nanoIR2 system by Anasys Instruments, equipped with a Quantum Cascade Laser tunable in the 900-1900 cm-1 range, covering the Amide I and Amide II bands of proteins. When the sample absorbs energy from light beam, it expands and the amplitude of the deflection oscillation of the AFM cantilever (AFM-IR signal) measures the energy absorbed by the material below the tip. The samples studied in this work are single patches of purple membrane deposited on ultra-flat template stripped gold substrates. Combining topography and the AFM-IR maps at different wavelengths, we can clearly identify single purple membranes, corresponding to ~5 nm-thick flakes which exhibit a strong absorption at the frequency of the Amide-I (1660 cm-1) but are almost undistinguishable from the substrate at a frequency away from the Amide-I peak. The near-field spectra obtained on single cell membranes with a lateral resolution of ~30 nm are in good agreement with what obtained with standard Fourier-transform-IR transmission in liquid and with diffraction-limited micro-spectroscopy. Minor differences are attributed to the effect of hydration, conformation and electric field orientation on the IR spectra. Our results confirm the feasibility of detecting the absorption spectrum at the few bR molecules level with the AFM-IR technique.

10111-14, Session 3

Evidence of amplitude and frequency modulation in a terahertz comb from intensity correlation measurements

Ileana-Cristina Benea-Chelmus, Markus Rösch, Giacomo Scalari, Mattias Beck, Jérôme Faist, ETH Zürich (Switzerland)

Only recently, a novel type of intensity autocorrelator in the time-domain has been reported for the Terahertz frequency range. The technique is based on fast electro-optic sampling in a double beam configuration and its temporal resolution is ultra-fast, as short as only few hundreds of femtoseconds. In particular, the self-referencing character of the technique is suitable for any type of source, including free-running sources. These unique characteristics enable therefore the investigation of the output profile of Terhertz Quantum Cascade Laser based Frequency Combs, with typical roundtrip times of few tens of picoseconds. The output dynamics of such devices have been investigated theoretically by Maxwell-Bloch equations and experimentally using Shifted Wave Interference Fourier Transform Spectroscopy. In this work, we present the results of the direct measurement of intensity autocorrelations of a Terahertz comb around 2.5 THz, when operated in the comb and high-noise regime, with radio-frequency beatnotes of 800 Hz and few MHz, respectively. We find the laser to be both amplitude- and frequency-modulated in both regimes, with a modulation ratio of the intensity of roughly 90 percent.The technique might come to use in future for the measurement of free-running pulses at Terahertz frequencies with high temporal resolution.

10111-15, Session 3

Electromagnetic field confinement in the gap of germanium nanoantennas with plasma wavelength of 4.5 micrometers

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Plasmonic nanoantenna designs are quickly evolving in the direction of practical molecular sensing applications hence their wavelength range is being extended from the visible towards the mid-infrared. The main problem in extending plasmonic confinement to the mid-IR is that metals behave very similarly to a perfect conductors in many mid-infrared designs. Here we designed and fabricated bowtie nanoantennas made of bottom-up assembled “metallic germanium” with very high free electron density and plasma wavelength of 4.5 microns. The 250 nm thick germanium films are obtained by molecular beam epitaxy in a bottom up approach, where nearly-identical two-dimensional phosphorus doped layers are repeatedly stacked at short distances in the third, vertical dimension. This value is 20 times smaller than the mid-infrared wavelength used in the experiment of 5.8 microns. The dielectric function of such “metallic” Ge is determined by IR spectroscopy and a plasma wavelength of 4.5 microns is found. The bowtie angle of 8.5 degrees and the length of 1 micron were chosen with the help of finite-difference time-domain simulations. Using a near-field infrared nanoimaging technique, based on the resonantly-enhanced photothermal expansion under quantum cascade laser illumination of an atomic force microscope tip, we demonstrate the existence of hotspots with dimensions of the order of 100 nm, 20 times smaller than the wavelength. The present results open the way to advanced plasmonic field-confinement designs with doped semiconductors.

10111-16, Session 4

Interband cascade lasers with longer wavelengths *(Invited Paper)*

Chadwick L. Canedy, Michael V. Warren, Charles D. Merritt, William W. Bewley, Chul Soo Kim, U.S. Naval Research Lab. (United States); Mijin Kim, Sotera Defense Solutions (United States); Igor Vurgaftman, Jerry R. Meyer, U.S. Naval Research Lab. (United States)

While interband cascade lasers (ICLs) have demonstrated room temperature continuous wave (cw) operation throughout the ? ≈ 3-6 ?m spectral band, most developmental work to date has focused on the shorter end of that range. As a step toward addressing the suitability of ICLs for low-power applications beyond 6 ?m, we report the implementation of new 7-10 stage designs for ICLs emitting at ? = 4.6-6.1 ?m. Whereas some cladding layers were composed entirely of InAs/AlSb superlattices, others employed hybrid designs that combined thinner superlattices with n+-InAsSb layers whose heavy doping provided electron plasma confinement (as recently demonstrated by U. Oklahoma). The pulsed room temperature threshold

for devices with ? = 4.8 microns was 220 A/cm2, the lowest ever reported for a semiconductor laser emitting at this wavelength or longer. While no previous NRL ICL emitting at ? > 4.2 microns had operated in pulsed mode up to 375 K, all three of the present structures with ? = 4.6-4.9 ?m operated at that temperature. The external differential quantum efficiencies (EDQEs) are also higher than earlier ICLs emitting at similar wavelengths, with values of 11-17% for 4.6-4.8 microns at 375 K that are nearly as large as those for ICLs emitting at much shorter wavelength. A device emitting at 5.7 microns exhibited a threshold of 450 A/cm2 and EDQE of 27% at 300 K, while at 6.0 microns the threshold was 660 A/cm2 with EDQE = 21%. The internal loss estimated from the slope efficiency increased from 6.4 cm-1 at 4.8 ?m to 13 cm-1 at 6.1 microns.

10111-17, Session 4

Single-frequency infrared tunable lasers with single-angle-facet gain chips for sensing applications

Ieva ?imonyte, Laurynas Andrulionis, Justinas Aleknavicius, Brolis Semiconductors UAB (Lithuania); Greta Naujokait?, Brolis Semiconductors (Lithuania); Edgaras Dvinelis, Augustinas Trink?nas, Mindaugas Greibus, Augustinas Vizbaras, Kristijonas Vizbaras, Brolis Semiconductors UAB (Lithuania)

The spectral range of (2 – 4) ?m is preferred for gas spectroscopy and non-invasive medical sensing applications based on tunable laser absorption spectroscopy (TDLAS). Strong absorption of environmental gasses and blood metabolites like lactates, glucose, urea etc., is the key feature that makes this wavelengths region so attractive. The main requirements for latter applications include widely-tunable single-frequency source, operation in continuous wave (CW) at room temperature, sufficiently high-output power, and small size, which can all be realized in external cavity laser setup using low-cost gain chips and laser diodes as gain medium. For applications in spectral region of (1.9 – 2.5) ?m, type-I quantum wells (QWs) GaSb-based gain chips are ideal candidates, since they have already demonstrated excellent performance with low input threshold powers, broad bandwidth, and CW output powers of tens of miliwatts.

In this work we present latest achievements on gain chips as sources for single-frequency tunable laser absorption spectroscopy and sensing. External cavity lasers based on Brolis Semiconductors (1.9 – 2.45) ?m wavelengths GaSb gain chips exhibited single mode laser emission with linewidths <100 kHz and output powers of >5 mW in the entire tuning range of >100 nm per chip. Continuous current tuning of 60 GHz and mode-hop free piezo tuning of 26 GHz were demonstrated. Additionally, we report on extended wavelengths range by demonstrating 3.4 ?m GaSb-based interband cascade and Brolis Semiconductors 0.85 ?m GaAs-based gain chips. Finally, experimental results on lactates sensing application in wavelengths range of (2.2 – 2.3) ?m will be presented.

10111-18, Session 4

On the way to improved active part of interband cascade lasers *(Invited Paper)*

Marcin Motyka, Wroclaw Univ. of Science and Technology (Poland)

Interband cascade lasers (ICLs) have already been proven as a promising mid-infrared (MIR) source desirable for many applications. Their potential originates mostly from unique operational characteristics as, e.g., single mode, continuous-wave and high power operation at elevated temperatures in the range from below 3 to about 6 μm, broad spectral tunability, and low threshold currents and hence small electrical power consumption when compared to the main competitor which are quantum cascade lasers.

The study has been focused on maximizing the optical transition oscillator strength (OS) via tailoring the electronic structure, the related strain and wave function engineering, as OS is the most critical parameter of the type II system, which can allow for compensating the intrinsic losses. For instance, we demonstrated that application of GaAsSb layers instead of GaInSb for confinement of holes switches the system to tensely strained. We have performed optical measurements on a set of type II QW samples utilizing a GaAsSb. The properly chosen widths of the layers, together with strain engineering provided by changing the arsenic content of the GaAsSb wells, allowed involving the light holes states into the fundamental optical transition. On one hand, this approach provided an additional degree of freedom for the emission wavelength transition oscillator strength tuning. Theoretical predictions of multiband kp theory have been experimentally verified by using photoluminescence and polarization dependent photoreflectance measurements. Obtained results open a pathway for practical realization of mid-infrared lasing devices with uncommon polarization properties including, for instance, polarization-independent mid infrared light emitters.

10111-19, Session 4

Long-wavelength GaSb interband cascade lasers *(Invited Paper)*

Sven Höfling, Anne Schade, Julius-Maximilians-Univ. Würzburg (Germany); Robert Weih, Julius-Maximilians-Univ. Würzburg (Germany) and nanoplus GmbH (Germany); Martin Kamp, Julius-Maximilians-Univ. Würzburg (Germany)

Interband Cascade Lasers (ICLs) are semiconductor laser sources in the mid-infrared spectral region. In the GaSb material system they can cover the ~2.7 μm to ~5.7 μm wavelength range operating in continuous wave mode and are therefore suitable for tunable laser absorption spectroscopy (TLAS) for detecting gases with absorption lines in this wavelength region like hydrocarbons. Beyond 5.7 μm important gases like nitrogen oxides have strong absorption lines making long wavelength GaSb ICLs interesting. We summarize our recent development of long wavelength ICLs optimized by reducing the number of electron injector quantum wells in the active region. The devices emit at 6 μm and they are capable of operating in continuous wave mode at room temperature, with pulsed mode characteristic temperatures of 51K and threshold current densities of 623A/cm2.

10111-20, Session 4

Type-II quantum wells for active regions of interband cascade mode-locked lasers

Mateusz Dyksik, Wroclaw Univ. of Science and Technology (Poland)

Interband cascade lasers (ICLs) have already been proven as a promising mid-infrared (MIR) source desirable for many applications. Their potential originates mostly from unique operational characteristics as, e.g., single mode, continuous-wave and high power operation at elevated temperatures in the range from below 3 to about 6 μm, broad spectral tunability, and low threshold currents and hence small electrical power consumption when compared to the main competitor which are quantum cascade lasers.

Interband cascade mode-locked lasers as a source of radiation are of great interest for dual-comb spectroscopy, where two mode combs with a slightly different spacing are used to sample a wide spectral range. While this is in principle possible with two Fabry-Perot lasers, the stable phase relation between the modes in a mode-locked device offers significant advantages for the practical implementation of dual comb spectroscopy. Passive mode-locking can be achieved by the insertion of a saturable absorber into the laser resonator. In semiconductor lasers, the saturable absorber can be realized by the application of reverse bias, which in case of ICL requires very careful band structure engineering since alignment of the levels in the minibands used to carrier transport depends on the polarity and the

magnitude of the internal electric field. In addition to possible applications in mode-locked lasers, engineering of the active regions towards smaller oscillator strength is also beneficial for Q- or gain switched lasers.

In this work, we present results of theoretical modeling in the framework of eight-band k•p theory of the ICLs' band structure under external electric field performed in order to investigate the effect of the bias value and direction, i.e. from normal lasing conditions as in the gain section to the reversed bias of the absorber part. We present several solutions of the respectively modified type-II QWs of InAs/(In,Ga)(As,Sb)/AlSb materials' system which allow obtaining the demanded lifetime (oscillator strength) ratio in the two parts of the mode-locked laser.

10111-21, Session 4

Pressure-dependent properties of type-II InAs/GaInSb mid-infrared interband cascade light-emitting devices

Zoe L. Bushell, Igor P. Marko, Stephen J. Sweeney, Univ. of Surrey (United Kingdom); Chul Soo Kim, Charles D. Merritt, William W. Bewley, Michael V. Warren, Chadwick L. Canedy, Igor Vurgaftman, Jerry R. Meyer, U.S. Naval Research Lab. (United States); Mijin Kim, Sotera Defense Solutions, Inc. (United States)

Interband cascade lasers (ICLs) are a promising light source for the mid-infrared (mid-IR) spectral range. However, for certain applications such as spectroscopic techniques for chemical sensing and non-invasive disease diagnostics, a broadband incoherent radiation source such as an LED may be more desirable. Here we investigate both ICLs and interband cascade light emitting devices (ICLEDs). The ICLEDs follow the example of ICLs by cascading multiple active stages in series to improve efficiency and increase output power, but without an optical cavity to provide feedback.

In this work we will present studies of these devices using high hydrostatic pressure techniques to determine the key efficiency limiting processes so that they might be mitigated. The application of hydrostatic pressure causes reversible changes to the band structure, increasing the energy of the conduction band gamma point and moving other key points in the band structure. This makes it a useful technique to probe recombination processes that depend on band gap and offsets, independently of temperature. For a laser dominated by CHCC Auger recombination, as is typical in narrow band gap devices for the mid-IR, one would expect a decrease in threshold current with increasing pressure, as the Auger process decreases with increasing band gap. However, the lasers studied here exhibit an increase in threshold current with pressure, indicating that other processes also play a significant role. We will discuss the relative contributions from Auger recombination and other processes such as defect-related recombination and carrier leakage in these devices, with respect to relevant modelling.

10111-22, Session 4

Monolithically-integrated mid-infrared interband cascade lasers and photodetectors *(Invited Paper)*

Hossein Lotfi, SM Shazzad Rassel, Lu Li, Cédric J. Corrége, Rui Q. Yang, Preston R. Larson, The Univ. of Oklahoma (United States); James A. Gupta, National Research Council Canada (Canada); Matthew B. Johnson, The Univ. of Oklahoma (United States)

The family of interband cascade (IC) IR devices includes: interband cascade lasers (ICLs), interband cascade IR photodetectors (ICIPs), and thermophotovoltaics (ICTPVs). To date, developments at the component level have resulted in power-efficient mid-IR ICLs with CW operation at room temperature and above as well as uncooled mid-IR low-noise and high-speed ICIPs. However, there has been little effort to integrate these devices on a single chip for an IR photonic system. Since an appropriately designed ICL can operate as an IR photodetector at zero bias, ICLs and ICIPs can be grown and fabricated on a single chip, enabling the on-chip integration of IR lasers and photodetectors for mid- and long-IR wavelengths.

We report the first demonstration of monolithically integrated mid-IR IC devices operating at room temperature. The unit consists of a monolithically integrated ICL and ICIP fabricated using focused ion beam (FIB) milling. The base structure is a type-I ICL with quaternary GaInAsSb active regions. The laser peak emission wavelength is 3.1 ?m at 20 ?C and the 10% cut-off wavelength of the corresponding ICIP is 3.3 ?m, which ensures sufficient photon absorption at the lasing wavelength. For a laser/detector unit (at 20 ?C) with a 12 ?m gap between laser mirror and detector, the open-circuit voltage of the ICIP is 1.06 V and its short-circuit current is 106 ?A, resulting from the laser emission (2.6 mW/facet). These preliminary results demonstrate the practical application of integrated IC devices for high-temperature, high-bandwidth and power-efficient on-chip sensors and optical communication mid-IR photonic systems.

10111-23, Session 4

Background subtraction in Fourier-domain mobility spectrum analysis for resolving low-mobility carriers *(Invited Paper)*

Boya Cui, Matthew Grayson, Northwestern Univ. (United States)

Narrow gap semiconductors and superlattices relevant to optoelectronics often host multiple conducting species, such as electrons and holes, requiring a mobility spectral analysis (MSA) method to separate contributions to the conductivity. Here, a least-squares MSA method is introduced: the QR-algorithm Fourier-domain MSA (FMSA). Like other MSA methods, the FMSA sorts the conductivity contributions of different carrier species from magnetotransport measurements, using a least-squares fitting algorithm to arrive at a best fit to the experimentally measured longitudinal and Hall conductivities. This method distinguishes itself from other methods by using the so-called QR-algorithm of linear algebra to achieve rapid convergence of the mobility spectrum as the solution to an eigenvalue problem, and by alternately solving this problem in both the mobility domain and its Fourier reciprocal-space. The result accurately fits a mobility range spanning nearly four orders of magnitude (? = 300 to 1,000,000 cm2/Vs) using a data resolution of 80 logarithmically spaced mobility points from ? = 100 to 1,000,000 cm2/Vs. This method resolves the mobility spectra as well as, or better than, competing MSA methods while also achieving high computational efficiency, requiring less than 30 seconds on average to converge to a solution on a standard desktop computer.

10111-24, Session 5

Terahertz optoelectronic sources and detectors *(Keynote Presentation)*

Iwao Hosako, National Institute of Information and Communications Technology (Japan)

In the terahertz (THz) frequency range, there are lots of options for sources and detectors even based on opto-electronic techniques. In this presentation, mapping of generation (Quantum Cascade Laser, Traveling Wave Tube, THz Frequency comb) and detection techniques (Quantum Well Infrared Photodetector, Backward Diode, Hot electron Bolometer Mixer) of THz signals and its subsystem applications (Spectral Measurement, Wireless Communication, Gas Sensing) will be shown. Based on the several mappings of the THz device techniques, prospective views of THz device technology and applications will be discussed.

10111-25, Session 6

Room temperature optomechanical detection of THz waves *(Invited Paper)*

Yanko Todorov, Chérif Belacel, Stefano Barbieri, Djamal Gacemi, Ivan Favero, Carlo Sirtori, Univ. Paris 7-Denis Diderot (France)

I will report on a novel type of detection of THz waves, based on optomechanical effects in a sub-wavelength metamaterial resonator. Our device consists of a metallic split-ring resonator is supplemented with a cantilever element. The device is thus sensitive to the mechancial action of THz waves. I will present systematic studies with a THz quantum cascade laser that allow assessing the performance of the device as a detector, that features an NEP of 1nW/sqrt(Hz) at 1MHz modulation frequency. I will also talk about the perspectives to decrease the NEP, potentially to the value of commercially available bolometers.

10111-26, Session 6

Sub-wavelength THz resonators for ultra-fast THz detection *(Invited Paper)*

Bruno Paulillo, Stefano Pirotta, Stéphane Guilet, Paul Crozat, Ctr. de Nanosciences et de Nanotechnologies (France); J.-M. Manceau, N. Zerounian, A. Degiron, I. Sagnes, G. Beaudoin, Ctr. de Nanosciences et de Nanotechnologies, Univ. Paris Sud, CNRS (France); G. Xu, Shanghai Institute of Technical Physics (China); Lianhe H. Li, Edmund H. Linfield, Giles A. Davies, Univ. of Leeds (United Kingdom); Raffaele Colombelli, Ctr. de Nanosciences et de Nanotechnologies (France)

Quantum-well infrared photo-detectors (QWIPs) are promising candidates in the quest for ultra-fast THz quanutum detectors. To date, the performances of THz-QWIPs are limited by the dark current, which is related to the device size. An effective strategy to improve this technology is to reduce the device active surface, without sacrificing its ability to efficiently collect the incoming radiation. Developing sub-wavelength THz QWIPs could lead to lower dark currents and also ultra-fast responses.

In this contribution we demonstrate arrays of QWIPs with extremely sub-wavelength active-core dimension of the order of ?0/50 (?eff/15,considering the effective ? inside the material). This extreme sub-wavelength size motivates the term “meta-atom”. The key idea is to exploit a miniaturized RF antenna as a coupler element to efficiently feed THz radiation (?=100-200 μm) into an ultra-subwavelength (4 μm) QWIP active core.

Current-voltage characterizations under dark and illumination conditions from a 300K blackbody have been performed to probe the meta-atom detector electrical contact scheme and to estimate the background-limited infrared performance (BLIP) temperature. A very low dark current (nA) flows in the device, which is promising in view of the reduction of the detector’s noise. The BLIP temperature is ≈ 8-10K and the responsivity is ≈10A/W, in agreement with literature.

Photocurrent spectra have been acquired and they show a relatively broad detection peak centred around 3 THz, spanning the 2-4 THz band.

The experimental measurement of the S-parameters show a 3dB cutoff beyond 40 GHz, promising an ultra-fast detector response. The ultrafast modulation behaviour of the detector will be also discussed.

10111-27, Session 6

Spectroscopy and mapping of resonant fields in terahertz plasmonic resonators *(Invited Paper)*

Oleg Mitrofanov, Univ. College London (United Kingdom); Zhanghua Han, Ctr. for Terahertz Research, China Jiliang Univ. (China); Fei Ding, Sergey I. Bozhevolnyi, Ctr. for Nano Optics, Univ. of Southern Denmark (Denmark); Igal Brener, John L. Reno, Sandia National Labs. (United States)

Plasmonic terahertz (THz) resonators have emerged as a flexible system for enhancing and exploring strong light-matter coupling. These resonators also provide well-defined field orientation, sub-wavelength size and relatively high Q-factors. The strong field confinement inside the resonator however limits access to the internal fields essential for investigations of light-matter coupling. We propose and demonstrate a method for mapping of confined fields inside plasmonic THz resonators. We use the aperture-type scanning near-field THz microscopy to access strongly confined fields of excited resonant modes with spatial resolution of 3-5 ?m (~?/100). Combined with the THz time-domain spectroscopy technique, the near-field method allows us to perform spectroscopic studies and investigate the field evolution inside the resonator. This experimental method opens doors to studies of strong light-matter coupling at THz frequencies in single plasmonic resonators.

10111-28, Session 6

On-chip terahertz dual-comb source based on quantum cascade lasers *(Invited Paper)*

Giacomo Scalari, Markus Rösch, Gustavo F. Villares, Lorenzo Bosco, Mattias Beck, Jérôme Faist, ETH Zürich (Switzerland)

Terahertz quantum cascade lasers (THz QCL) are a very promising source for efficient frequency comb generation at terahertz frequencies. They do not only provide an output power of the order of milliwatts but are also covering a large spectral bandwidth. Octave spanning devices have recently been reported by our group. They provide a very low intrinsic dispersion due to the flat gain curve and the flat losses of the resonator. This allows frequency comb operation up to more than 600 GHz bandwidth with standard broadband metal-metal waveguide Fabry-Pérot QCLs. Frequency combs at terahertz frequencies are especially interesting for spectroscopic applications employing the powerful dual-comb setup. Such a setup requires a fast detector which is difficult to get with a sufficient sensitivity at terahertz frequencies. We present here an alternative approach, which does not need a fast detector but rather uses one of the two THz QCL frequency combs as an ultrafast multiheterodyne detector integrating local oscillator (LO) and detector in one single device. Two laser ridges are fabricated on the same chip at a distance of 500 um. Part of the light from the sample laser is coupled into the LO laser via the metallic ground plane. The downconverted multiheterodyne beatnote can be measured through the laser power supply line with a bias Tee. The obtained dual-comb covers a bandwidth of 630 GHz with a central frequency of 2.5 THz. The frequency comb spacing was analysed using frequency counting techniques revealing an accuracy down to _frep=fcarrier 10^(-12) at the carrier frequency of 2.5 THz.

10111-29, Session 6

InGaAs and InAs THz quantum cascade lasers *(Invited Paper)*

Karl Unterrainer, Technische Univ. Wien (Austria)

Terahertz quantum cascade lasers are the most successful sources for terahertz radiation. Output powers and efficiencies are constantly improving which increases their potential for applications. Here, we report our work towards even higher performance by studying active regions based on InGaAs and InAs. Because of the lower effective mass higher gain and higher operating temperatures are expected. We study different barrier materials and designs. We use symmetric structures to investigate the influence of interface roughness and doping position. Despite the epitaxial more demanding structures encouraging output powers and operating temperatures have been achieved.

10111-30, Session 6

Ultrashort terahertz pulse generation from a dispersion-compensated modelocked quantum cascade laser *(Invited Paper)*

Sukhdeep Dhillon, Feihu Wang, Hanond Nong, Juliette Mangeney, Jérôme Tignon, Lab. Pierre Aigrain (France)

Modelocked semiconductor lasers for ultrashort pulse generation are an underpinning technology throughout the optical and near-infrared regions. However, in the terahertz THz range, modelocking of THz quantum cascade lasers (QCLs) has only resulted in large pulse widths in the range of 10 to 20 picoseconds. In this work we break this limit and realise a monolithic device to realise ultra-short THz pulses. This is based on dispersion compensation of an active modelocked THz QCL with an integrated Gires-Tournois interferometer (GTI). This permits stable pulse generation with pulse widths as short as 4 ps, considerably shorter than the state-of-the-art. The concepts of this work opens up the possibility of sub-picosecond and single cycle THz pulses to be attained from a compact semiconductor device.

10111-31, Session 7

Photon pair sources using silicon photonic microring resonators and silicon microelectronic components *(Invited Paper)*

Shayan Mookherjea, Univ. of California, San Diego (United States); Marc Savanier, Univ. of California, San Diego (United States) and Luxtera, Inc. (United States)

Integrated opto-electronic microchip devices are being shown to benefit quantum optics, and standard silicon photonic components such as micro-resonators can, in particular, be effectively used for room-temperature photon-pair generation and heralded single photon generation at telecommunications wavelengths using less than a milliwatt of optical pump power. The incorporation of micro-electronics components into the setup or the chip itself further improves performance, e.g., allowing stable photon-pair generation over a wide variation in temperature, or shaping light from a cw pump laser diode into pulses of the appropriate width.

Progress has also been made in verifying the entanglement of the photon-pair, and in studying and improving its spectral properties by measuring and controlling the quantum Joint Spectral Intensity (JSI), an important quantity which is the squared-magnitude of the wavelength-resolved amplitude coefficient of the two-photon state. One goal of ongoing research is to achieve a close-to-factorizable state for photon-pair generation using spontaneous four-wave mixing in silicon microring resonators. Another goal is generation of two-photon states with different entanglement properties, which are expected to have different JSIs and vice-versa, so that control of the JSI may result in creating a pair-source whose entanglement properties can be varied on-demand. While measurement of classical analogues of the JSI is fairly easy, measurement of the true quantum-mechanical JSI is hard, and offers exciting inter-disciplinary research opportunities at the intersection of optics and signal processing.

10111-32, Session 7

Second-order nonlinearities in strained silicon photonic structures *(Invited Paper)*

Pedro Damas, Xavier Le Roux, Mathias Berciano, Guillaume Marcaud, Carlos Alonso-Ramos, Ctr. de Nanosciences et de Nanotechnologies (France); Daniel Benedikovic, Ctr. for Nanoscience and Nanotechnology (France); Delphine Marris-Morini, Ctr. de Nanosciences et de Nanotechnologies (France); Eric Cassan, Laurent Vivien, Ctr. de Nanosciences et de Nanotechnologies (France)

Silicon photonics is being considered as the future photonic platform for low power consumption optical communications. However, silicon is a centrosymmetric crystal, i.e. silicon doesn't have Pockels effect. Nevertheless, breaking the crystal symmetry of silicon can be used to overcome this limitation. This crystal modification is achieved by depositing a SiN high-stress overlayer.

In this work, we present recent developments on the subject taking into account parasitic effects including plasma dispersion effect and fixed charge effect under an electric field. We theoretically and experimentally investigated Pockels effect in silicon waveguides and last results will be presented.

10111-33, Session 7

GaAsP nanowires and nanowire devices grown on silicon substrates *(Invited Paper)*

Yunyan Zhang, Univ. College London (United Kingdom); Martin Aagesen, Gasp Solar ApS (Denmark); Ana M. Sanchez, Univ. of Warwick (United Kingdom); Richard Beanland, The Univ. of Warwick (United Kingdom); Jiang Wu, Huiyun Liu, Univ. College London (United Kingdom)

The nanowire (NW) structure with a diameter in nanometer scale offers a way to integrate the lattice and the thermal expansion coefficient mismatched material systems by efficiently relaxing the strain with in a length of a few monolayers. The integration of III–V materials on a Si platform can thus be achieved in the form of III-V NWs monolithically grown on silicon substrates. GaAsP NWs with a band gap which can cover the wavelength ranging from green (548 nm at 300 K) to near-infrared (864 nm at 300 K), is one of the most promising III-V compound semiconductor for photovoltaics and visible emitters. We have achieved the self-catalyzed GaAsP NW growth on Si substrates with high uniformity. The NW shows almost pure zinc-blende structure with very low defect density. The P composition of the NW can be tuned between 0 and 75%, which gives us more freedom in design NW device structures. A power conversion efficiency over 10% has been achieved from a single GaAsP NW SC which sets a new world record for single NW solar cells. We developed the repeatable growth of self-catalyzed GaAsP nanowires on SiO2 patterned Si(111) substrates and makes us one step closer to the large-area NW SC fabrication. In addition, defect-free GaAs/GaAsP nanowire quantum dots have been demonstrated with narrow single dot emission by varying the P composition in GaAsP nanowires.

10111-34, Session 7

Polarization-free integrated gallium-nitride photonics *(Invited Paper)*

Can Bayram, Richard Liu, Univ. of Illinois at Urbana-Champaign (United States)

Gallium Nitride (GaN) semiconductors offer unique opportunities in

ultraviolet to infrared photonics thanks to their direct and tunable wide bandgap. However, inherit polarization fields hinder the electron and hole recombination in the "quantum wells" of such photonic devices. This "polarization" effect is so pronounced in LEDs that reduced efficiencies under high injection currents – a phenomenon known as "droop" – is imminent in all devices. Polarization-free approach - as in cubic phase GaN - is essential for droop-free LEDs. Here we investigate the effects of nano-patterning parameters on cubic phase formation and demonstrate a method of forming pure cubic phase gallium nitride (GaN) on Si. First, U-shaped grooves with various patterning parameters are fabricated on CMOS-compatible Silicon (100) substrates. Next, metalorganic chemical vapor deposition is used to facilitate GaN growth in the grooves. Depending on the patterning parameters, a partial to complete hexagonal-to-cubic phase transition of GaN on the surface is reported. Finally, the resulting hexagonal and cubic phase materials are investigated via room (280 K) and low (5.7 K) temperature cathodoluminescence. A crystallographic model is proposed to explain the phase transition of GaN in such U-grooves. Experimental studies agree well with the crystallographic model, suggesting a unique relationship between GaN deposition thickness, etch depth, and opening width for complete cubic phase GaN surface coverage. Electron backscatter diffraction experiments validate single phase cubic GaN coverage that agrees well with the modelling.

10111-35, Session 7

Evolution of phase difference and absolute phase of interacting waves under SHG of high-intensive femtosecond pulse *(Invited Paper)*

Vyacheslav A. Trofimov, Dmitry M. Kharitonov, Mikhail V. Fedotov, M.V. Lomonosov Moscow SU (Russian Federation)

SHG is used in many practical applications such as a substance diagnostics, and imaging of various processes as well as for frequency conversion. Well known that SHG is used also for a generation of tripled frequency wave due to mixing of optical radiation at basic frequency with optical radiation at doubled frequency. In this case an important role plays a relation between phase of interacting waves with basic frequency and doubled frequency. Therefore, a derivation of corresponding law of phases evolutions are urgent problem. Below we provide such derivation for a SHG of high intensive femtosecond pulse with taking into account an influence of a cubic nonlinear response on the frequency doubling.

Using the frame-work of long pulse duration approximation and plane wave approxima-tion as well as an original approach we derive the solution of Schrödinger equations de-scribing the SHG for femtosecond pulse without using the approximation of basic wave energy non-depletion. It should be stressed, that the frequency conversion in conditions under consideration possesses multy-stability: there are many modes of SHG efficiency. We derive an evolution of phase of waves for each of the modes. The derived formulas are verified by computer simulation on the base of using the corresponding Schrödinger equations.

10111-36, Session 8

Merging scattering near-field microscopy and self-mixing interferometry in quantum cascade lasers *(Keynote Presentation)*

Gaetano Scamarcio, Lorenzo L. Columbo, Massimo Brambilla, Maurizio Dabbicco, Univ. degli Studi di Bari Aldo Moro (Italy); Carlo Rizza, Univ. dell'Insubria (Italy); Alessandro Ciattoni, CNR-SPIN (Italy); Vezio Bianchi, Enrico Dardanis, Miriam S. Vitiello, Istituto Nanoscienze (Italy); Edmund H. Linfield, Lianhe H. Li, Univ. of Leeds (United Kingdom); Clemens Liewald, Fritz Keilmann, Ludwig-Maximilians-Univ. München (Germany)

The inherent stability of quantum cascade laser against optical feedback is exploited in a number of self-mixing interferometry (SMI) configurations, new phenomena and applications. Besides numerous metrological applications, this lead to: i) controlling the terahertz emission of THz QCLs by reconfigurable photo-generated anisotropic metamaterials; ii) free carrier imaging and coherent imaging. Feeding back into either mid-IR or THz QCL cavities the modulated radiation scattered by an AFM tip tapping on a sample surface is bringing SMI in the realm of deep sub-wavelength spatial resolutions (~40nm) and simpler self-detection (detectorless) s-SNOM configurations, with groundbreacking implications for mid-IR and expecially THz near-field imaging.

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10111-37, Session 8

Beyond the Hall effect: Novel transport characterization techniques for 21st century optoelectronic materials *(Keynote Presentation)*

Matthew Grayson, Northwestern Univ. (United States)

The standard method for characterizing mobility and density in semiconductors has remained largely unchanged since the van der Pauw 4-point method was introduced in the 50's. However, modern electronic materials – including narrow gap semiconductors, superlattices for infrared detectors and lasers, and parallel conducting layers of different doping – can have multiple species of carriers with anisotropic conductivities and possibly even non-uniform doping, requiring more sophisticated magnetotransport methods. Recent breakthroughs allow us to fully characterize all essential parameters in such materials. A comparison of +B and –B longitudinal magnetoresistances can be used to quantify doping gradients in a conducting layer. A QR algorithm for mobility spectral analysis can rapidly deduce an entire spectrum of conducting electrons and holes within a wide mobility range ? = 102 – 106 cm2/Vs. And careful magnetotransport analysis can separately extract the in-plane and cross-plane anisotropic conductivity tensor of a lightly-doped or intrinsic superlattice layer, even when shorted by a highly doped substrate contact. In this talk, I will summarize these breakthroughs in characterization methods that overcome a variety of challenges posed by modern optoelectronic materials.

10111-38, Session 9

InAs/InAsSb superlattice structure tailored for detection of the full midwave infrared spectral domain

Quentin Durlin, Jean-Philippe Perez, Rémi Rossignol, Jean-Baptiste Rodriguez, Laurent Cerutti, Institut d'Électronique et des Systèmes (France); Bruno Delacourt, Johan ROTHMAN, Cyril Cervera, CEA-LETI (France); Philippe Christol, Institut d'Électronique et des Systèmes (France)

Recently, Ga-free InAs/InAsSb type-II superlattices (T2SL) have shown promising performance with minority carrier (MC) lifetimes measured over than 5µs at 80K in the midwave infrared (MWIR) spectral domain. This high MC lifetime values have been obtained because of the type-II band alignment of Ga-free SL structure where electrons and holes are confined in their own InAs and InAsSb layers, respectively. However, this strong delocalization of the carriers decreases the overlap wavefunction, weakens the absorption and then the radiometric performances of the MWIR detector.

In this communication, we studied the Ga-free T2SL period, thickness and antimony composition, in order to define an optimised structure, combining electrical and optical properties, suitable for high performance MWIR photodetector. The SL structures were fabricated by MBE on n-type GaSb substrate and exhibited cut-off wavelength between 5µm and 5.5µm at 80K. The samples were first compared by time-resolved photoluminescence (TRPL) and absorption measurements from 80K to 250K. Next, electrical (dark current) and photoresponse measurements were performed on Ga-free SL detectors and results obtained were compared with each other and with others Ga-containing SL devices. The study made demonstrates the strong influence of the Ga-free SL period on the performances of MWIR SL photodetectors.

10111-39, Session 9

Long-wavelength interband cascade infrared photodetectors towards high temperature operation

Lin Lei, Lu Li, Hao Ye, Hossein Lotfi, Rui Q. Yang, Matthew B. Johnson, Jeremy A. Massengale, Tetsuya D. Mishima, Michael B. Santos, The Univ. of Oklahoma (United States)

With a discrete absorber architecture that circumvents the diffusion length limitation, interband cascade infrared photodetectors (ICIPs) based on the InAs/GaSb/AlSb material system have the potential for high device performance at room temperature and above in the long wavelength infrared (LWIR) region. In this work, we present a systematic study of four different ICIP structures. One is a single absorber barrier detector, while the other three are multi-stage ICIPs with four, six and eight discrete absorbers. The cutoff wavelength of these detectors was around 8~12 µm from 78 to 300 K. We observed the benefits of the multi-stage ICIPs over the one-stage device in terms of lower dark current density and higher detectivity (D*). The advantage of high temperature operation of ICIPs was also demonstrated. The one-stage detectors operated at temperatures up to 250 K, while the six- and eight-stage ICIPs were able to operate at 300 K with D* higher than 1.0?10^8 Jones. The thin absorber in each stage of the ICIPs ensured the efficient collection of photo-generated carriers when the minority carrier lifetime was reduced at high temperatures. Also, the noise was suppressed with more stages. The D* for these ICIPs at 200 K was larger than 1.0?10^9 Jones at 8 µm, which is higher than the corresponding value of photovoltaic HgCdTe detectors at similar cutoff wavelengths.

10111-40, Session 9

Extended cut-off wavelength nBn detector utilizing InAsSb/InSb digital alloy absorber

Alexander Soibel, David Z. Ting, Cory J. Hill, Anita M. Fisher, Linda Höglund, Sam A. Keo, Sarath D. Gunapala, Jet Propulsion Lab. (United States)

Mid-wavelength infrared (MWIR) detectors covering 3-5µm atmospheric transmission windows are of great interest for NASA Earth Science missions. The recently demonstrated nBn or XBn barrier photodetectors offer many advantages for realization of high performance infrared imagers (IR). In our research we investigated a novel approach to extend a cut-off wavelength of Sb-based nBn detectors. We incorporated a series of single InSb monolayer into InAsSb bulk that allowed to realize a digital alloy absorber with an extended cut-off wavelength of ? = 4.6 µm at T = 200 K. The cut-off wavelength extension to 4.6µm is technologically important for realization of detectors covering CO2 absorption line at 4.26µm. At the same time, the constructed digital alloy InAsSb/InSb is a fascinating material system that has an energy bandgap smaller that the random allow with the same material composition. The developed nBn detectors with 2µm thick absorber showed a temperature independent quantum efficiency QE≈0.45 for back-side illumination without antireflection coating. The dark current density was jd=5?10-6 A/cm2 at T = 150K, and increased to jd = 2 ?10-3 A/cm2 at T = 200K. At temperatures of T = 150K and below, the demonstrated photodetectors operate in background limited (BLIP) mode, with detectivity D*(?)=3-6x1011 (cmHz0.5/W) for the background temperature of 300K, and f/2 field of view.

10111-41, Session 9

InGaAs/GaAsSb type-II quantum well focal plane array with cutoff-wavelength of 2.5 um

Takahiko Kawahara, Kenichi Machinaga, Balasekaran Sundararajan, Kouhei Miura, Masaki Migita, Hiroshi Obi, T. Fuyuki, Kei Fujii, Takashi Ishizuka, Hiroshi Inada, Yasuhiro Iguchi, Sumitomo Electric Industries, Ltd. (Japan)

In the short wavelength infrared (SWIR) region, low cost, high responsivity focal plane array (FPA) are expected for many industrial applications such as mining, recycling plastic and remote monitoring of infrastructure. HgCdTe (MCT) is predominantly used for infrared imaging applications even in SWIR region. However, MCT is expensive and contains environmentally hazardous substances. Therefore, its application has been restricted mainly military and scientific use and was not spread to commercial use. InGaAs/GaAsSb type II quantum well structures are proposed as an attractive material for realizing low dark current. 320x256 FPA with cutoff-wavelength of 2.35?m was demonstrated for commercial use by our group. Moreover, we have successfully extended cutoff-wavelength up to 2.5?m comparably one of MCT in SWIR. InGaAs thickness in quantum wells was changed. In this report, we describe the operation of FPA with cutoff-wavelength of 2.5?m and mention the improvement of optical characteristics. Planar type pin-PDs with 250-pairs-InGaAs/GaAsSb quantum well absorption layer were successfully fabricated. The p-n junction was formed in the absorption layer by the selective diffusion of zinc. InGaAs layer which was adopted as a layer for adjusting concentration distribution of zinc, were grown on quantum wells. Electrical and optical characteristics of FPA or pin-PDs were investigated. Dark current was less than 2?A/cm2 at 213K, which showed diffusion current limited mode. This result means FPA using InGaAs/GaAsSb type-II quantum wells is a promising candidate for commercial applications.

10111-42, Session 9

Type-II InAs/GaSb superlattices for dual-color infrared detection

Linda Höglund, Rickard Marcks von Würtemberg, Hithesh K. Gatty, Anders Gamfeldt, Carl Asplund, Dan Lantz, Eric M. Costard, IRnova AB (Sweden)

IRnova has demonstrated excellent manufacturability of MW FPAs based on Type-II InAs/GaSb superlattices. MW-MW dual color detection has now been successfully demonstrated by using pixel filters fabricated on top of these FPAs. The pixel filters used in these FPAs were designed to transmit infrared radiation in the 3.5 um-4.1 um wavelength region and to completely block light shorter than 3.5 um. By comparing the signals of filtered and unfiltered pixels, excellent contrast between the two bands were obtained. This design concept offers a great flexibility to tailor the transmission window to any wavelength range within the 3-5 um wavelength region. In particular, this dual color detector concept has been used for gas detection of volatile organic compounds which have main absorption peaks at 3.3um.

10111-43, Session 10

Accelerating technology innovations by early understanding of fundamental and technology limitations of material synthesis and device operation *(Keynote Presentation)*

Jagmohan Bajaj, Philip Perconti, Meredith L. Reed, U.S. Army Research Lab. (United States)

Timely technology transition with minimal risk requires an understanding of fundamental and technology limitations of material synthesis, device operation and design controllable parameters. However, this knowledge based approach requires substantial investment of resources which, for low volume niche semiconductor technologies of DoD relevance, industry alone cannot justify simply because there is no significant return on investment. As a result, technology transition from S&T to product development is often expensive, delayed, and carries risks. The Army research Laboratory (ARL) is responding to this problem by establishing a Center for Semiconductor Materials and Device Modeling that brings together government, academia, and industry in a collaborative fashion to address fundamental research opportunities through its Open Campus initiative. This Center leverages combined core competencies of partner organizations; broad knowledge base in modeling, and its validation; sharing of computational, characterization, materials growth and device processing resources; project continuity; and 'extension of the bench' via exchange of researchers between affiliated entities. A critical Army technology is sensing in the infrared (IR) spectrum, where understanding of materials, devices and methods for sensing and processing IR information must continually improve to maintain superiority in combat. This presentation will look at historical evolution of IR technology and emphasize the urgency for understanding of material properties and device operation to accelerate innovation and shorten the cycle time, thereby ensuring timely transition of technology to product development and manufacturing.

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10111-124, Session 10

The linewidth of intersubband lasers *(Keynote Presentation)*

Mauro Fernandes Pereira, Sheffield Hallam Univ. (United Kingdom)

The linewidth of a conventional laser is due to fluctuations in the laser field due to spontaneous emission and is described by the Schalow-Townes formula. In addition to that, in a semiconductor laser there is a contribution arising from fluctuations in the refractive index induced by carrier density fluctuations. The later are quantitatively described by the linewidth enhancement or ? factor. The ? factor of intersubband lasers was initially expected to be zero. However, values ranging from -0.5 to 3 have been found experimentally. This paper resolves this controversy showing that counter rotating terms, usually ignored in simulations are the actual fundamental origin of nonzero ? at peak gain even without inclusion of nonparabolicity and manybody effects, which are however needed to explain negative values. For laser without inversion conditions, significant as a potential out of the box solution for the elusive room temperature operation of terahertz lasers, ? is found to be larger, but still at the same order of magnitude of conventional inverted medium lasers, thus ensuring their applicability to a huge number of spectroscopic applications which require sharp laser linewidths. [M.F. Pereira, The Linewidth Enhancement Factor of Intersubband Lasers: From a Two-Level Limit to Gain without Inversion Conditions, Applied Physics Letters 109, 222102 (2016)].

10111-44, Session 11

HgCdTe APDs for low-photon number IR detection *(Invited Paper)*

Johan Rothman, Eric D. de Borniol, Julie Abergel, Gilles Lasfargues, Bruno Delacourt, CEA-LETI (France); Arnaud Dumas, Fabien Gibert, Lab. de Météorologie Dynamique (France); Olivier Boulade, CEA-IRFU (France); Xavier Lefoule, SOFRADIR (France)

HgCdTe APDs have opened a new horizon in photon starved Infra-Red (IR) applications due to their exceptional performance in terms of high linear gain, low excess noise and high quantum efficiency. These characteristics have enabled single photon detection in the Mid-wave IR (MWIR range) and improved performances for a large range of applications where the detected information is mediated by a low number of photons in each spatial and/or temporal observation, such as active imaging, wavefront correction, free space optical communications, gas sensing LIDAR and quantum optics. The present communication will detail the present state of the art in terms of gain, excess noise factor, dark current and response time in HgCdTe APDs with different Cd composition and cut-off wavelengths. The obtained performance will be illustrated through application examples made with developed imaging arrays and single element detector dedicated to extract the spatial and/or temporal information in a photon flux.

10111-45, Session 11

Black silicon: a solution for near-infrared-enhanced imaging

Martin U. Pralle, Jutao Jiang, James E. Carey, Chris J. Vineis, Chintamani Palsule, SiOnyx LLC (United States)

Early investigations of Black Silicon in Harvard's Mazur lab revealed a new material with unique properties including high optical absorption and very high photoresponse. Since that time, SiOnyx has engineered this material to operate within the stringent confines of the CMOS image sensor process enabling advanced imaging capabilities. Today, we have demonstrated

imaging at light levels below 1 mLux (commonly recognized as moonless clear starlight) at 60 FPS with a 1.3MP CMOS image sensor. Sub mLux imaging is enabled by the combination of enhanced quantum efficiency in the near infrared together with state of the art low noise image sensor design. The quantum efficiency enhancements are driven by the integration of Black Silicon into the pixel architecture. The combined image sensor technology demonstrates a 10 fold improvement in infrared sensitivity over incumbent imaging technology while maintaining complete compatibility with standard CMOS image sensor process flows. Recent advances in backside illumination have further augmented the performance without degrading noise and dark current parameters. Applications include medical imaging, computational imaging, surveillance, nightvision, and 1064nm laser see spot. Imaging performance metrics will be discussed.

10111-46, Session 11

Advantages of strained-layer superlattice detectors for high-speed thermal events *(Invited Paper)*

Austin A. Richards, FLIR Systems, Inc. (United States)

Recent advances in commercial development of Strained-Layer Superlattice (SLS) detectors have given a boost to infrared camera applications in the longwave infrared spectrum. Traditionally, MCT or QWIP detector arrays were needed to image in the longwave infrared region of the spectrum. SLS detector arrays have a much wider spectral response and higher quantum efficiency compared to QWIP detectors, and offer greater uniformity than longwave MCT when the camera is first powered up. SLS detector arrays are also easier to make and operate than MCT, resulting in significant cost savings.

All these features are huge advantages when recording thermal imaging applications that are either "light starved" or else require large temperature dynamic range capability. Light starved applications include imaging very cold scenes (well below 0°C), where thermal IR backgrounds get very low, and imaging high-speed objects or dynamic scenes at lower temperatures. A good example of this would be a helicopter rotor blade which can have a tip approaching the speed of sound while remaining at ambient temperature.

High temperature dynamic range scenes also benefit from SLS detectors. These include rocket launches where the goal is to simultaneously image the cold hardbody and the hot plume. Such an image can be achieved in the LWIR part of the spectrum by taking a sequence of images at different exposure times and merging them into one high dynamic range (HDR) image. This kind of HDR imaging is difficult to achieve with a midwave camera, as it would have a more limited temperature range.

10111-47, Session 11

InAs/(GaSb,AlSb) and HgTe/CdTe superlattices: detector materials with topological properties *(Invited Paper)*

Philip C. Klipstein, SCD SemiConductor Devices (Israel)

Type II superlattices (T2SLs) based on alternating layers of InAs and GaSb exhibit rather unique properties, including a zero bandgap at a critical value of the layer thicknesses. In this respect, T2SLs bear a close relationship to the alloy, HgxCd1-xTe ("MCT"), where the bandgap vanishes at a critical value of the composition parameter, x. A 15 micron pitch T2SL Long Wave Infrared array detector has recently been developed by SCD, based on a new XBp barrier architecture and a new and robust passivation process. This detector is made entirely from III-V materials but exhibits performance comparable to high quality MCT detectors.

The SCD T2SL XBp detector contains both an InAs/GaSb active layer (AL) and an InAs/AlSb barrier layer. A k.p simulation method is described which can predict both the quantum efficiency and dark current with reasonable precision, from a basic definition of the superlattice period and the AL stack thickness. Results are compared with simulations for HgTe/CdTe superlattices. The method introduces a number of novel features including the use of an interface matrix, and a way of calculating the Luttinger parameters from standard reference values.

For layer thicknesses greater than the critical values, both InAs/GaSb/AlSb and HgTe/CdTe superlattices undergo a transition to a Topological Insulator (TI) phase. A graphene like dispersion is observed at the TI transition, and the TI phase exhibits unusual spin polarized transport and optical properties which may be useful in future spintronic and THz devices.

10111-48, Session 11

MTF and FPN measurements to evaluate midwave infrared T2SL focal plane arrays

Jean Nghiem, Julien Jaeck, Edouard Giard, Marcel Caes, ONERA (France); Jean-Baptiste Rodriguez, Philippe Christol, Institut d'Électronique et des Systèmes (France); Riad HAIDAR, ONERA (France); Eric M. Costard, IRnova AB (Sweden); Isabelle Ribet-Mohamed, ONERA (France)

Type-II superlattice (T2SL) has emerged as a new material technology suitable for high performance infrared (IR) detectors operating from NIR (2-3?m) to VLWIR (> 15?m) wavelength domains.

In this communication, we report the radiometric spatial characterization of a commercial MWIR (3-5?m) InAs/GaSb T2SL FPA (320x256 pixels with 30?m pitch). Modulation Transfert Function (MTF) measurements are realized using the self-imaging property (known as Talbot effect) of a grating illuminated by a plane wave. The main advantage of this technique is that no optics is required to project the pattern on the FPA : a Continuously Self Imaging Grating (CSIG) produces a non-diffracting spot array on the detector.

In addition, a new class of radiometric characterization called "correctability", or ability for FPA pixels to durably keep the same behavior when exposed to a given flux, has been investigated. A two points correction (TPC) has been calculated on the signal obtained by the FPA on the first day D0. The same gain and offset parameters have been applied to every data acquired on different days to obtain the Residual Fixed Pattern Noise (RFPN). As long as the RFPN remains inferior to the temporal noise, one may consider the non-uniformity correction (NUC) is still valid. This characterization highlights the strong stability of such T2SL FPA device, even 3 weeks after the initial .This confirms the potentiality of T2SL technology to compete with the currently high performance infrared photodetectors.

10111-50, Session 12

The room temperature ferromagnetic properties of dilute magnetic III-nitride semiconductor materials and quantum structures *(Keynote Presentation)*

C. Zhou, A. Ghods, V. Saravade, C. Ferguson, Ian T. Ferguson, Missouri Univ. of Science and Technology (United States)

In this presentation, the current theoretical and experimental status of transition metal and rare earth doped III-Nitrides are discussed and their suitability for room temperature spintronic applications is reviewed. Reports of room temperature ferromagnetism in these materials are complicated by disparate crystalline quality and phase purity, as well as conflicting theoretical predictions as to the nature of ferromagnetic behavior. For example, it is still not well understood whether the ferromagnetism derives from an intrinsic material property or from nano-scaled cluster distributions in the system. In addition, when ferromagnetism is observed it is not clear if it is free carrier mediated as there have only been a few reports of Anomalous Hall Effect and Circular Magnetic Dichroism measurements. In this work, III-Nitride materials and quantum structures have been grown by metal organic chemical vapor deposition doped with Mn, Fe, Cr and Gd. The predominant theoretical models and predictions for ferromagnetism in the III-Nitrides are compared with the available literature. In particular, the correlation of the structural, optical, and magnetic behavior in Dilute Magnetic III-Nitride Semiconductors are analyzed and compared to materials produced by other growth techniques. A complete understanding of these materials, and ultimately intelligent design of room temperature spintronic devices, will require an exploration of the relationship between the processing techniques, resulting transition metal or rare earth atom configuration, defects, electronic compensation and other physical properties..

10111-105, Session 12

New approaches to computing with photonics *(Keynote Presentation)*

Nasser N. Peyghambarian, Mark A. Neifeld, College of Optical Sciences, The Univ. of Arizona (United States)

Two new opportunities for optical computing will be reviewed. The first is an example of metaphoric computing. We will present theoretical analysis and experimental demonstration of an optical Ising machine based on a multicore fiber laser system governed by a generalized Ising Hamiltonian. The second is an example of algorithmic computing. We will describe an all-optical architecture that implements message passing on a large graphical model. Analysis of performance and noise tolerance together with experimental demonstration of key computing primitives will be presented.

10111-51, Session 13

Optical properties of long-wave infrared InAs/InAsSb superlattices *(Invited Paper)*

Arezou Khoshakhlagh, Linda Höglund, David Z. Ting, Sarath D. Gunapala, Jet Propulsion Lab. (United States)

Absorber material quality is critical for high performance infrared detectors. In order to achieve high material quality, detailed structural and optical characterization are necessary for the understanding of material limitations and optimization processes. Well calibrated material growth, material optimization and quality control procedures have enabled high-performance material development at the Jet Propulsion laboratory. The minority carrier lifetime is one of the important material characterization tools used in determining the potential device performance of infrared detectors, since it affects the dark current as well as the quantum efficiency. The lifetimes initially measured for InAs/GaSb type-II superlattices (SLs) were considerably shorter than the lifetimes of HgCdTe (~80 ns for MW InAs/Ga(In)Sb SLs). However, significant improvements of the minority carrier lifetime have been recently observed for Ga-free type-II InAs/InAsSb SLs with lifetimes, at around 9 ?s for a MW SL (cut-off wavelength ~5.4 ?m) and ~420 ns for a long wavelength (LW) SL (cut-off wavelength ~8.4 ?m). As the wavelength increases toward long wave and very long wave the lifetime of this material system decreases. Therefore, to optimize the InAs/InAsSb SL based materials, detailed study of mechanisms limiting the lifetime in these SLs is needed. In this presentation, detailed study of temperature dependence of the minority carrier lifetime in LW InAs/InAsSb SLs is reported.

10111-52, Session 13

Capacitance voltage profiling to determine doping in InAs/GaSb LWIR SL photodetector structures *(Invited Paper)*

Rémi Rossignol, Jean-Baptiste Rodriguez, Quentin Durlin, Hocine Aït-Kaci, Jean-Philippe Perez, Institut d'Électronique et des Systèmes (France); Frédéric MARTINEZ, Fernando GONZALES-POSADA, Institut d Electronique et des Systèmes (France); Philippe Christol, Institut d'Électronique et des Systèmes (France)

The last past years, it has emerged a new generation of antimonide-based (Sb-based) structures for infrared detection called "Barrier Structures". These structures present advanced designs where the accurate control of doping of each layers is essential in order to manage the electrical behavior of the device. However, the doping control of grown epi-layers remains an open problem for the fabrication of complex structures by molecular beam epitaxy (MBE). Hall-effect measurement is a well-known efficient way to determine doping of layers on insulating substrate. Unfortunately, there is no insulating GaSb substrate on which the Sb-based layers can be grown. Consequently, there is a need in a quick and efficient approach to routinely evaluate doping of Sb-based layers grown on GaSb substrate.

This communication reports capacitance-voltage C(V) measurements, performed on MIS structures, in order to determine doping of layers which will be the different layers of complex Sb-based barrier structure for infrared photodetector devices. Several Sb-based structures have been investigated, made of different periods of InAs/GaSb and InAs/InAsSb superlattices as absorbing layers and different periods of InAs/AlSb and GaSb/AlSb superlattices as barrier layers. Results obtained were analysed and compared with each other. Finally, C(V) measurements were performed on an complete structure such as InAs/GaSb superlattice pBn photodetector and compared with equivalent pin photodiode.

10111-53, Session 13

Toward a 2D high-performance multi-channel system for time-correlated single-photon counting applications *(Invited Paper)*

Pietro Peronio, Giulia Acconcia, Alessandro Cominelli, Ivan Rech, Massimo Ghioni, Politecnico di Milano (Italy)

Time-Correlated Single Photon Counting (TCSPC) is acknowledged as one of the most effective techniques for measuring weak and fast optical signals, since it provides very high temporal resolution and sensitivity. Nevertheless, the long acquisition time needed to perform a measurement it's still the main drawback.

To overcome this limitation, multidimensional TCSPC systems have been developed, but they still suffer for a strong trade-off between performance and number of channels: the higher the number of channels, the poorer the performance.

In this work we present the design of a complete TCSPC acquisition system which is meant to overcome this trade-off.

Since the best state-of-the-art detectors and sensing circuits cannot be built on the same chip, different technologies have been employed in order to achieve the best performance from both sides, therefore Through Silicon Vias (TSVs) are used to connect a custom technology SPAD array to a CMOS pick-up circuit.

Since a high number of detectors will cause the count rate to saturate due to the limited transfer rate of a PC, the maximum throughput has been set to 10 Gb/s, well beyond the state of the art. As a consequence, the number of acquisition chains has been tailored on the affordable throughput, and a dynamic-routing logic connects the detectors to this lower number of

acquisition channels. Five fast Time-to-Amplitude Converters (TACs), able to reach 80 MConv/s, have been designed in order to get high temporal resolution along with low dead time.

Finally, the preliminary results obtained so far will be presented.

10111-54, Session 14

Nonlinear plasmonics in nonperturbative hydrodynamic model *(Invited Paper)*

Alexey V. Krasavin, Giuseppe Marino, Pavel Ginzburg, Gregory A. Wurtz, Anatoly V. Zayats, King's College London (United Kingdom)

In this talk, we start from vivid examples of nonlinear plasmonics, such as the formation of plasmon-solitons and nonlinear mode coupling in individual metallic nanoparticles (which leads to a novel criterion for SHG at the nanoscale) and then progress to full time-domain hydrodynamic description of nonlinear electron dynamics in metallic nanostructures. The robust non-perturbative numerical model implementing and solving it without any simplification reveals a key contribution to the nonlinear effects defined by the interplay between the topology of the nanostructure and the nonlocal response of the metal. The quantum pressure term of the Fermionic gas responsible for nonlocal effects in the nonlinear hydrodynamic model leads to the emergence of fractional nonlinear harmonics and results in broadband coherent white-light generation. The investigation of Archimedean spirals, lacking any reflection and rotational symmetries, illuminated by 50 fs pulses, provides the clear signature of 6 nonlinear harmonics, favouring this structure over cylinders, as well as coherent white light generation. The described processes present a novel class of nonlinear phenomena in metallic nanostructures determined by nonlocality of electron response. Second harmonic generation from plasmonic hyberbolic metamaterials will also be discussed.

10111-55, Session 14

Dielectric metasurfaces for shaping of classical and quantum light *(Invited Paper)*

Dragomir N. Neshev, The Australian National Univ. (Australia)

The concept of Huygens metasurfaces has recently emerged as a powerful platform for complete manipulation of light properties, including phase, amplitude, polarisation, and even colour. Their operation is based on the interference of the electric and magnetic dipolar responses of the constituent metasurface elements, called meta-atoms, such that they can only scatter in forward direction, while back-scattering is inhibited. Dielectric Huygens metasurfaces stand out as a prominent example, due to their negligible optical losses and easy fabrication. Such dielectric metasurfaces are composed of small high-refractive-index nano-particles, which exhibit Mie-type resonances of both electric and magnetic origin and comparable strength. By designing the geometry of the individual meta-atoms it is possible to exactly match the spectral position of these resonances, thus enabling unitary transmission through the Huygens metasurface, while simultaneously being able to control the phase of transmitted light in the full range of 0-2ϖ.

This talk will overview the fundamental designs and principles of operation of such dielectric metasurfaces, as well as the plethora of their functionalities, including frequency selectivity, wavefront shaping, and polarization control. In particular, we demonstrate experimentally beam shaping in complex holographic shapes and vectors beams with azimuthal/radial polarisations with near unity transmission efficiency and operating over a broad spectral range. Importantly, we will present some of their recent applications in nonlinear light sources, biosensing, and characterisation of bi-photon and multi-photon entangled states.

10111-56, Session 14

Functional photonic nanostructures based on Mie-resonant semiconductor nanoparticles *(Invited Paper)*

Isabelle Staude, Friedrich-Schiller-Univ. Jena (Germany)

Nanoparticles composed of high refractive index semiconductors can support strong localized Mie-type resonances of electric and magnetic multipolar character that can be tuned by the nanoresonator geometry [1]. In addition, such semiconductor nanoresonators can exhibit very low absorption losses at optical frequencies. Based on these unique optical properties, semiconductor nanoresonators represent versatile building blocks of functional photonic nanostructures with tailored optical properties.

This talk will provide an overview of our recent advances in controlling the generation and propagation of light with dielectric nanostructures composed of silicon or other high-index semiconductor nanoresonators.

First, I will focus on passive and linear silicon metasurfaces designed to impose a spatially variant phase shift onto an incident light field, thereby providing control over its wave front. Based on the simultaneous excitation of electric and magnetic dipole resonances, silicon nanoresonators can be tailored to emulate the behaviour of the forward-propagating elementary wavelets known from Huygens' principle [2]. This concept allows for the realization of various wave front shaping devices with high transmittance efficiency, full phase coverage, and a polarization insensititve response [3,4].

I will then discuss how we can utilize semiconductor nanoresonators for tailoring spontaneous emission from nanoscale light sources as well as for the manipulation of nonlinear effects in semiconductor nanoparticles.

[1] I. Staude et al., ACS Nano 7, 7824 (2013).

[2] M. Decker et al., Adv. Opt. Mater. 3, 813 (2015).

[3] K. E. Chong et al., Nano Lett. 15, 5369–5374 (2015).

[4] K. E. Chong et al., ACS Photonics 3, 514-519 (2016).

10111-57, Session 14

Second harmonic generation in AlGaAs nanoantennas *(Invited Paper)*

Costantino De Angelis, Univ. degli Studi di Brescia (Italy); Valerio Gili, Univ. Paris 7-Denis Diderot (France); Luca Carletti, Davide Rocco, Andrea Locatelli, Univ. degli Studi di Brescia (Italy); Lavinia Ghirardini, Politecnico di Milano (Italy); Ivan Favero, Univ. Paris 7-Denis Diderot (France); Carmen Gomez Carbonell, Aristide Lemaitre, Lab. de Photonique et de Nanostructures, Ctr. National de la Recherche Scientifique (France); Marco Finazzi, Michele Celebrano, Politecnico di Milano (Italy); Giuseppe Leo, Univ. Paris 7-Denis Diderot (France)

Metal-less nanophotonics has recently raised an increasing interest because the optical response of high permittivity dielectric nanoparticles exhibits negligible dissipative losses and strong magnetic multipole resonances in the visible and near-infrared. We propose here all-dielectric Al0.18Ga0.82As-on-AlOx nanocylinders, on which we measure second harmonic generation (SHG) with a conversion efficiency up to 7?10^-5 for a 1.6 GW/cm^2 pump in the optical telecom wavelength range. Our samples were fabricated from a [100] GaAs wafer, with a 400nm layer of Al0.18Ga0.82As on top of an aluminum-rich substrate. The result is an array of nanopillars on an aluminum-oxide (AlOx) substrate. The linear and nonlinear optical response of such nanoantennas are modelled by using frequency-domain finite element simulations. We numerically predict a SH conversion efficiency up to 6?10^-5 for a pump wavelength between 1500 nm and 1700 nm. To experimentally investigate the nonlinear properties of the fabricated nanopillars we excited them with an ultrafast Erbium-doped fiber laser centered at 1550 nm (150 fs pulses, 80 MHz repetition rate). SHG signals were collected from an array of nanocylinders with radius varying from 175 to 225 nm, using single-photon avalanche photodiodes. The theoretically predicted dependence of the detected SHG on the radius size of the nanocylinders singles out three resonances for the SHG nanocavity modes excited at three specific radii size, in striking agreement with the experimental results.

These results show the huge potential of AlGaAs nanoantennas for nonlinear nanophotonic applications.

10111-58, Session 14

Purcell factor and multiexcitonic-emission in a single-emitter patch nanoantenna *(Invited Paper)*

Amit Raj Dhawan, Institute of Fundamental and Frontier Sciences (China) and Univ. Pierre et Marie Curie (France); Juan Uriel Esparza, Univ. Pierre et Marie Curie (France); Micheal Nasilowski, Ecole Supérieure de Physique et de Chimie Industrielles de la Ville de Paris (France); Chérif Belacel, Ctr. Development Technologies Avancées (Algeria); Catherine Schwob, Laurent Coolen, Benoit Dubertret, Univ. Pierre et Marie Curie (France); Pascale Senellart, Univ. Paris-Saclay (France); Agnès Maître, Univ. Pierre et Marie Curie (France)

Plasmonic nano-antennas provide broadband spontaneous emission control by confining light on highly sub-wavelength volumes. We realize a plasmonic patch antenna by positioning a emitter within a ultrathin slab of dielectric limited by an optically thick gold layer and a thin gold patch. A single CdSe/CdS colloidal quantum dot is deterministically located just in the center of the antenna by an original in situ optical lithography protocol [1]. Depending on the dimension of the patch antenna and the emitter orientation, different Purcell factors could be achieved leading to different optical properties. For moderate Purcell factors, patch nanoantennas are plasmonic directive single photon sources. For higher Purcell factors, the spontaneous emission acceleration makes the multiexciton radiative recombination more efficient than Auger non radiative recombination. Emission of photons due to multiexcitons recombination could be observe at very short time scale. Such antennas can be very efficiently excited. Such antenna appear to be extremely bright as their luminescence exceed by more than one order of magnitude the one of single nanocrystals.

References:

[1] Dousse, A. et al. Controlled light-matter coupling for a single quantum dot embedded in a pillar microcavity using far-field optical lithography. Phys. Rev. Lett. 101, 267404 (2008).

[2] C. Belacel, B. Habert, F. Bigourdan, F. Marquier, J-P. Hugonin, S. Michaelis de Vasconcellos, X. Lafosse, L. Coolen, C. Schwob, C. Javaux, B. Dubertret, J-J. Greffet, P. Senellart, A. Maître, Controlling spontaneous emission with plasmonic optical patch antennas, Nanoletters 13 1516 (2013)

10111-59, Session 15

Linear and nonlinear optical behavior of epsilon near zero metamaterials: opportunities and challenges *(Invited Paper)*

Xin Li, Monika Pietrzyk, Univ. of St. Andrews (United Kingdom); Daniele Faccio, Heriot-Watt Univ. (United Kingdom); Carlo Rizza, Alessandro Ciattoni, Consiglio Nazionale delle Ricerche (Italy); Andrea Di Falco, Univ. of St. Andrews (United Kingdom)

Epsilon Near Zero (ENZ) metamaterials exhibit a linear permittivity that approaches zero at specific wavelengths. The seminal research papers in this area focused on a number of exotic effects, including peculiar waveguiding geometries, control of the radiation pattern and imaging applications.

Here we specifically focus on ENZ effective media obtained layering materials with positive and negative permittivity, with individual subwavelentgh thickness. In this configuration, specific components of the electromagnetic field, propagating through such media, experience a considerable relative enhancement. This feature underpins a number of unique optical effects both at linear and nonlinear regimes.

In particular, here we demonstrate the fabrication of effective media with artificial chirality that depends on the ENZ condition and the optically induced dynamic transition from dielectric to metallic behaviors of ENZ media.

Finally we present and discuss methods to overcome the inherent limits of the ENZ approach, which include the unavoidable losses associated to the near zero permittivity condition and the extreme form birefringence inherited form the sample topology.

10111-60, Session 15

Resonant nano-antennas for shaping thermal emission of light *(Invited Paper)*

Riad Haïdar, Patrick Bouchon, ONERA (France)

Metal nanoantennas make it possible to manipulate the light, and in particular to control its absorption. According to Kirchhoff's law, emissivity equals absorptivity and nanoantennas may become light sources operating by thermal emission. These sources exhibit properties that deviate from those of the ideal blackbody described by Planck's law.

We will show that it is possible to develop a metasurface based on metal-insulator-metal nanoantennas, wherein each antenna has dimensions smaller than the wavelength, and acts as a transmitter at given polarization state and wavelength of light, independent of the adjacent antennas. It is thus possible to obtain spatial, spectral and polarization control of the emitted light, and thus to encode complex images. Other nanoantennas concepts will be presented, such as optical Helmholtz resonators.

10111-61, Session 15

Using plasmon-induced resistance changes in a tunable metal grating for all-electronic readout

Borui Chen, Alec Cheney, Tianmu Zhang, Tim Thomay, Alexander N. Cartwright, Univ. at Buffalo (United States)

The rise of integrated plasmonic sensor technology shows potential to overcome the limitations of semiconductor based devices. However, in these plasmonic devices, a major challenge is the intrinsic loss introduced by electron scattering processes in the metals used. Here, we employ a strategy [1] to take advantage of these losses to design, fabricate and characterize a metal grating based micro-sensor. Our device integrates optical plasmonic response with electronic readout to realize spectral and polarization-dependent detection-based on scatter-induced losses. This plasmon induced change in resistance can be understood as the coupling between the applied current with localized and delocalized surface plasmons which leads to increased inelastic electron-electron scattering and electron-phonon interaction. By varying geometric parameters such as the period and thickness of our structures, we are able to create a spectral response that enhances the electronic signal ratio of the TE and TM modes by a factor of three. This enhancement was realized in a silver grating with an area of 100um x 50um, a period of 300nm, a thickness of 25nm and a spectral resonance at 532nm. Our platform demonstrates the feasibility of

an all-electronic, CMOS-compatible plasmonic sensor which offers tunability across an ultra-wide bandwidth from visible to IR wavelengths, limited only by the plasmon resonance of the metals used. Preliminary results using pulsed excitation suggests possible applications in ultrafast detection.

Reference:

[1] J. B. Herzog, M. W. Knight, and D. Natelson, Nano Lett. 14, 499 (2014). http://dx.doi.org/10.1021/nl403510u

10111-62, Session 15

Harnessing blackbody radiation with metasurfaces *(Invited Paper)*

Emilie Sakat, Leo Wojszwzyk, Jean-Paul Hugonin, Jean-Jacques Greffet, François Marquier, Institut d'Optique Graduate School (France)

In the last 15 years, many ideas have completely changed our perspective on what can be done with incandescent sources: highly directional sources [Nature 416, 61 (2002)] as well as quasi monochromatic sources [Phys.Rev. Lett. 107, 045901 (2011)] have been demonstrated. Electrical modulation of the absorptivity has allowed modulating the thermal emission at a rate of 600 kHz by a stack of quantum wells [Nature Mat. 13, 928 (2014)].

We present here a novel approach, introducing a generalized Kirchhoff law valid for anisothermal bodies. To illustrate the concept, we will take the example of a metasurface consisting in an array of half-wavelength nanoantennas. By inserting a small volume of absorber in the gap of a dimer antenna, it is possible to enhance the power extracted from the small hot volume by more than three orders of magnitude. This can be achieved provided that the absorber has been properly designed in order to verify a critical coupling condition with the antenna. It follows that a cubic volume with a side of 150 nm inserted in a gold linear antenna with length 4 μm and square section with side 150 nm. The enhancement can be understood either in terms of Purcell enhancement or in terms of impedance matching. In order to produce a practical emitter, a periodic array of antennas can be fabricated, which results in a metasurface for IR emission.

10111-63, Session 15

Mid-IR to THz polaritonics: realizing alternative IR materials *(Invited Paper)*

Joshua D. Caldwell, U.S. Naval Research Lab. (United States)

The field of nanophotonics is based on the ability to confine light to sub-diffractional dimensions. Up until recently, research in this field has been primarily focused on the use of plasmonic metals. However, the high optical losses inherent in such metal-based surface plasmon materials has led to an ever-expanding effort to identify, low-loss alternative materials capable of supporting sub-diffractional confinement. Beyond this, the limited availability of high efficiency optical sources, refractive and compact optics in the mid-infrared to THz spectral regions make nanophotonic advancements imperative. One highly promising alternative are polar dielectric crystals whereby sub-diffraction confinement of light can be achieved through the stimulation of surface phonon polaritons within an all-dielectric, and thus low loss material system. Due to the wide array of high quality crystalline species and varied crystal structures, a wealth of unanticipated optical properties have recently been reported. This talk will discuss recent advancements from our group including the realization of localized phonon polariton modes, the observation and exploitation of the natural hyperbolic response of hexagonal boron nitride. Beyond this, methods to improve the material lifetime and to induce additional functionality through isotopic enrichment and hybridization of optical modes will also be presented.

10111-64, Session 15

InGaAs-based GMR photodetector: a step towards the fourth generation *(Invited Paper)*

Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France)

Invited abstract.

The extreme light confinement provided by nanophotonic structures pushes toward revisiting the photodetector design. On the other hand introducing absorbing layers in nano-resonators demands dedicated electromagnetic design. This context opens the way for performance improvements and new functionalities, introducing the fourth generation of photo-detectors with promising features such as ultra-thin absorbing layers, device area much smaller than its optical cross-section and carved optical response. In this talk, I present a GMR InGaAs photo-detector dedicated for FPA applications, illustrating this global design and the cross-linked properties of the optical and semiconductor structures.

In this "guided mode resonator", the semiconductor stack works as an optical guide. Its bottom part is structured in order to generate the first order diffraction modes in the semiconductor. Adjusting the coupling between the optical modes of the guide and those of the grating, allows optimizing this structure for various applications as optimum absorption at 1.55 ?m or in the SWIR band [M. Verdun et al, Appl. Phys. Lett. 108 053501 (2016)].

The photodiode is based on an InP/InGaAs double heterojunction. The small thickness of the InGaAs absorbing layer (100 – 200 nm) allows suppressing the diffusion currents as well as reducing the generation-recombination currents in the space charge layer. It will be shown that the minimum value of the dark current is not necessarily reached for the thinnest absorbing layers.

As a result, experimental data show at ? = 1.55 ?m an external quantum efficiency of 75% and a specific detectivity of up to 1013 cm.√Hz.W-1.

10111-65, Session 15

Plasmon-assisted energy transfer between fluorophores located several microns apart *(Invited Paper)*

Valentina Krachmalnicoff, Institut Langevin (France)

Energy transfer between two fluorophores (called donor and acceptor) is a key process in a variety of phenomena, spanning from biology to physics. It is often a very inefficient process, unless at distances of a few nanometers. In such cases the underlying phenomenon is Förster Resonant Energy Transfer, which is widely used in life-science for measuring nanometer scale distances and changes in distances. We report on the observation of energy transfer between fluorophores located several microns apart on a silver thin film [Phys. Rev. Lett. 116, 037401 (2016)]. The energy transfer is assisted by surface plasmons (SPPs) propagating on the top of the film. The donor (fluorescent bead) is excited by a laser and decays by launching a SPP that transfers its energy to the acceptor (organic molecules) in the ground state. The acceptor, located up to 7 μm apart, is excited by the SPP, decays and emits fluorescent photons that are detected. To go towards quantum phenomena, we then studied plasmon-assisted energy transfer between a quantum dot (QD) and the molecules inside a latex bead. To improve the efficiency, donor and acceptor are coupled to a silver nanowire. As a consequence of the energy transfer, the molecules inside the bead show the same blinking behaviour as the QD, which is a signature of the temporal correlation between donor and acceptor fluorescence. This experiment can pave the way towards the exploration of very interesting phenomena, such as cooperative emission, or the realization of a quantum communication platform with integrated systems.

10111-66, Session 16

Advances in vertical external-cavity surface-emitting lasers (VECSEL) for new wavelength generation *(Keynote Presentation)*

Mahmoud Fallahi, College of Optical Sciences, The Univ. of Arizona (United States)

In the last decade optically-pumped vertical external cavity surface emitting lasers (VECSEL) have been investigated as multi-watt, tunable sources with applications in defense, medical, remote sensing and communication. Single mode, high power CW outputs in excess of 10W have been widely reported from single-chip InGaAs/GaAs/GaAsP structures over a wide wavelength range of around 900-1200 nm. Output power as high as 100W was also reported using large-area pumping VECSEL. One unique feature of VECSEL compared to other semiconductor lasers is the access to the high intracavity circulating power, allowing new functionalities such as wavelength tuning, mode-locking and nonlinear wavelength generation. Multi-watt blue, green and yellow sources have been efficiently demonstrated by our team and others through intracavity second harmonic generation. Two-color VECSELs have also proven to be efficient for intracavity sum or difference frequency generation. Recently we proposed and demonstrated a new two-color VECSEL cavity, called T-cavity, allowing the generation and co-axial emission of widely tunable two color lasers. Such high-power, individually controllable two-color lasers have great flexibility for efficient generation of new wavelengths by second harmonic (SHG), sum frequency generation (SFG) or difference frequency generation (DFG), allowing the generation of target wavelengths that are typically hard to generate directly from semiconductor gain structures. In this talk an overview of VECSEL design and fabrication will be presented. Latest developments in high power, high brightness VECSELs will be reported. The generation of new wavelength through intracavity nonlinear conversion in the UV- far IR will be discussed and future opportunities will be presented.

10111-67, Session 17

Managing high-power densities in highly nonlinear nanostructures made of wide bandgap semiconductors *(Invited Paper)*

Aude Martin, Thales Research & Technology (France) and Lab. de Photonique et de Nanostructures, Ctr. National de la Recherche Scientifique (France) and Univ. Paris-Saclay (France); Sylvain Combrié, Thales Research & Technology (France); Fabrice Raineri, Isabelle Sagnes, Lab. de Photonique et de Nanostructures, Ctr. National de la Recherche Scientifique (France) and Univ. Paris-Saclay (France); Alfredo De Rossi, Thales Research & Technology (France)

Sub-wavelength semiconductor structures, particularly photonic crystals, have shown remarkable nonlinear properties, owing to the strong confinement and slow light propagation. Compared to the optical fiber, the nonlinear coupling parameter is about 10^6 times larger, allowing efficient nonlinear interaction in short waveguides. Consequently, ultra-fast all-optical signal processing techniques, based on nonlinear fiber optics, have been demonstrated in a photonic chip and could be integrated photonic integrated circuits.

The optical power density reaches here extremely high levels, typically 50 GW/cm^2, when accounting for the slow light "spatial compression" effect. This puts a formidable stress on the photonic nanostructure, particularly when operating in the continuous wave mode. Here we will report a new class of nonlinear photonic nanostructures based on wide-gap semiconductors. They are able to sustain these extremely high optical power densities. This gives access to extreme nonlinear dynamics on chip, which is promising for fundamental studies, as well as large average power, which, in turns, is crucial for practical use of all-optical functions.

The specific case of efficient parametric interactions and four wave mixing will be discussed in detail, along with implications on phase-sensitive amplification and hyper parametric oscillations. This result is also relevant to a broader range of situations, where it is desirable to achieve very large power densities in photonic circuits, e.g. microwave photonics.

10111-68, Session 17

GaAs/AlGaAs waveguiding wavelength conversion devices *(Invited Paper)*

Takashi Kondo, RCAST, The Univ. of Tokyo (Japan)

I will present out research on waveguiding wavelength conversion devices utilizing quadratic optical nonlinearities of compound semiconductors. The introduced device configurations include periodically inverted quasi-phase matching (QPM) devices, thin-rectangular high-indexcontrast birefringence phase matching devices, and zigzag waveguide 4-bar QPM devices. Special emphasis will be placed on GaAs/AlGaAs QPM waveguides fabricated based on epitaxial

growth technique (sublattice reversal epitaxy) we have developed for growing spatially inverted semiconductors. Wavelength conversion performances of our recent GaAs/AlGaAs QPM devices will also be given.

10111-69, Session 17

AlGaAs on-insulator nonlinear photonics *(Invited Paper)*

Minhao Pu, Yi Zheng, Erik Stassen, Luisa Ottaviano, Elizaveta Semenova, Hao Hu, Francesco Da Ros, Leif K. Oxenløwe, Kresten Yvind, Technical Univ. of Denmark (Denmark)

AlGaAs can be very efficient nonlinear material in the 1550nm range by adjusting the composition to avoid two-photon absorption. However, high confinement, very low loss and efficient dispersion engineering is needed to fully reap the advantages. We will present AlGaAs on insulator as an efficient platform for nonlinear integrated photonics. Low loss nanowire waveguides on SiO2 has been fabricated and characterized. High nonlinearity > 660/(W m), losses <1.5dB/cm and Q factors for microring resonators >10^5 have been achieved. This has enabled Kerr comb generation with thresholds less than 10mW, flat four-wave mixing over >750nm and the first wavelength conversion of >1Tbaud optical signals. AlGaAs on sapphire has also been fabricated by direct waferbonding to achieve lower MIR losses and better thermal dissipation. Microring resonators with Q>10^5 has also been fabricated in this platform.

http://arxiv.org/abs/1509.03620

10111-70, Session 17

Widely-tunable near-IR monolithic coherent source *(Invited Paper)*

Alice Bernard, Marco Ravaro, Ivan Favero, Univ. Paris 7-Denis Diderot (France); Michel Garcia, Olivier Parillaud, Bruno P. Gérard, III-V Lab. (France); Jean-Michel Gérard, Commissariat à l'Énergie Atomique (France); Giuseppe Leo, Univ. Paris 7-Denis Diderot (France)

The InP and GaAs platforms, well known for their mature laser-diode technology, allow for efficient optical frequency conversion on chip thanks to their strong quadratic nonlinearity and broad transparency range. Based

on these features, we report on the design and preliminary characterization of a monolithic widely tunable near-IR parametric source.

Two spontaneous parametric down conversion (SPDC) sources are studied. The first one relies either on a GaAs/AlGaAs laser diode operating as a pump at 1 μm or on an InGaAsP/InP diode with laser emission at 1.55 μm, with intracavity SPDC from 1.8 to 2.3 μm or around 3 μm, respectively. In the second one, two superposed cavities for laser emission and SPDC are coupled through a vertical tapered coupler. These designs are accompanied by a characterization of InGaAsP refractive index in the near-IR range up to 3 μm, where this alloy has never been studied despite its common use in the telecom range.

This work is promising for a continuous-wave parametric source on chip, with wavelength tunability up to 500 nm and a peak power of a few mW, enough for out-of-the-lab spectroscopy applications.

10111-71, Session 17

Directional quasi-phase matching AlGaAs waveguide microresonators for efficient generation of quadratic frequency combs

Maria Parisi, Iolanda Ricciardi, Simona Mosca, Istituto Nazionale di Ottica (Italy); Natalia Morais, Univ. Paris 7-Denis Diderot (France); Tobias Hansson, Institut National de la Recherche Scientifique (Canada); Stefan Wabnitz, Univ. degli Studi di Brescia (Italy); Giuseppe Leo, Univ. Paris 7-Denis Diderot (France); Maurizio De Rosa, Istituto Nazionale di Ottica (Italy)

Waveguide microresonators provide small-volume confinement and resonant enhancement that greatly improve the efficiency of nonlinear processes. GaAs and its compounds, with their strong quadratic nonlinear response, are one of the most promising material platforms for integrated nonlinear photonic circuits operating in the infrared range. Although it lacks natural birefringence, the directional dependence of nonlinear coupling on the crystal symmetry in GaAs can be exploited for directional quasi-phase matching (DQPM) of nonlinear processes by a proper design of the waveguide geometry [1].

To achieve efficient generation of quadratic optical frequency combs in resonant-enhanced second-harmonic generation [2], we propose a guided-wave modular design which extends the applicability of DQPM to a wide class of AlGaAs microresonators, which are generally suitable for highly efficient second-order nonlinear processes. Geometric tailoring of the dispersive features of the device releases the constraint on waveguides curvature, and allows for reduced bending losses compatible with long-path, high-quality resonators. By combining a sequence of arc- and S-shaped segments in a closed loop, which we fabricate in an AlGaAs suspended nanowire technology, modular DQPM resonant configurations can be obtained. Supported by numerical simulations, we show the possibility to generate frequency combs with pump thresholds in the microwatt range, and teeth separations in the 10-1000 GHz range.

[1] S. Mariani, A. Andronico, A. Lemaître, I. Favero, S. Ducci, and G. Leo, Opt. Lett. 39, 3062 (2014).

[2] I. Ricciardi, S. Mosca, M. Parisi, P. Maddaloni, L. Santamaria, P. De Natale, and M. De Rosa, Phys. Rev. A 91, 063839 (2015).

10111-72, Session 18

Nonlinear optics, optomechanics, and antibacterial coating by graphene oxide *(Invited Paper)*

Carlotta Ciancico, Maria Chiara Braidotti, Instituto Dei Sistemi Complessi (Italy) and Sapienza Univ. di Roma (Italy); Silvia Gentilini, Sapienza Univ. di Roma (Italy) and Instituto Dei Sistemi Complessi (Italy); Radjove Prizia, Neda Ghofraniha, Luca Angelani, Istituto dei Sistemi Complessi (Italy) and Sapienza Univ. di Roma (Italy); Valentina Palmieri, Univ. Cattolica del Sacro Cuore (Italy); Francesca Bugli, Marco De Spirito, Maurizio Sanguinetti, Università Cattolica del Sacro Cuore (Italy); Massimiliano Papi, Univ. Cattolica del Sacro Cuore (Italy); Claudio Conti, Istituto dei Sistemi Complessi (Italy) and Sapienza Univ. di Roma (Italy)

Our activity is focused on nonlinear optics and optomechanics in graphene and graphene oxide. We have studied thermally induced deflection of graphene layers, measured by atomic force microscopy. Laser-induced deflection can lead to the realisation of dynamical membranes, moved by light patterns realised using a spatial light modulator. We have also investigated the effect of laser printing on graphene oxide gels. A thermally induced supercavitation effect arises when using a high power pulsed laser. This effect allows the realisation of patterns printed on the GO gel, in which the GO nanosheets are more exposed than in the rest of the surface. The different morphology of the substrate affects bacterial and viral growth. Cell integrity analysis by scanning electron microscopy and nucleic acids release show bacteriostatic and bactericidal effect, up to 90%. We also report on the thermophoretic nonlinear optical effect and saturable absorption in samples made by graphene oxide sheets in suspension.

10111-73, Session 18

Transition metal dichalcogenide material growth and devices for sensing applications *(Invited Paper)*

Patrick Kung, Sourav Garg, Joseph L. Waters, Abu Shahab Mollah, Seongsin Margaret Kim, The Univ. of Alabama (United States)

Atomically-thin transition metal dichalcogenides (TMDCs) are topological materials with physical characteristics of great interest for the realization of nano-electronic and photonic devices, with promising applications for chemical and biological sensing. For example, molybdenum disulphide (MoS2) and tungsten disulfide (WS2) are semiconductors whose bandgap changes from indirect to direct as a result of the disappearance of the inversion symmetry when the material is reduced into a 2D, sub-nanometer monolayer form. Although TMDC monolayers were originally and are continuing to be widely realized through mechanical exfoliation, increasing effort is being devoted to the synthesis of these materials using chemical vapor deposition in order to achieve larger area monolayers in a more controllable manner.

In this work, we present the large area growth of monolayer thin films of TMDCs, such as MoS2 and WS2, by low-pressure chemical vapor deposition in an oxygen-free environment that does not need active sulfurization. A combination of electron microscopy, atomic force microscopy, Raman and photoluminescence spectroscopy was employed to evaluate the monolayer-vs.-multilayer nature of the films, as well as their optical characteristics. Interdigitated patterned devices were realized to allow characterization of the material electrical transport properties as well as their electro-optic response under an optical stimulus. Based on the obtained results, we will further discuss the impact of these monolayer materials for robust nano-electronic and photonic device applications.

10111-74, Session 18

Terahertz devices exploiting bi-dimensional materials and heterostructures *(Invited Paper)*

Miriam S. Vitiello, CNR-NANO (Italy)

Bi-dimensional nano-materials and related heterostructures are establishing themselves as new photonic and electronic materials with huge potential in a variety of applications ranging from saturable absorbers to optical modulators, from optical communication components when placed on chip with flat integrated optical circuits to spintronics, from near field components to high-resolution sensing and fast tomography. Their peculiar band-structure and electron transport characteristics, which can be easily manipulated via layer thickness control, suggest they could also form the basis for a new generation of high-performance devices operating in the Terahertz frequency range (1-10 THz) of the electromagnetic spectrum. This paper will review our latest achievements in THz nano-photonics and nano electronics based on 2D nano-materials and discuss future perspectives of this rapidly developing research field.

10111-75, Session 18

Intra- and interband conductivity of epitaxial graphene close to the Dirac point *(Invited Paper)*

Juliette Mangeney, S. Massabeau, Matthieu Baillergeau, T. Phuphachong, Lab. Pierre Aigrain (France); C. Berger, Univ. Grenoble Alpes (France); Walter A. de Heer, Georgia Institute of Technology (United States); Sukhdeep Dhillon, Jérôme Tignon, L. A. de Vaulghier, Robson Ferreira, Lab. Pierre Aigrain (France)

Graphene is emerging as an attractive material for applications in future high-frequency electronics, ultrafast optoelectronics and photonics owing to its unique properties such as high carrier mobility and ultra-broadband optical absorption. The main challenge for realizing the application potential of graphene is to obtain large graphene crystals of high quality. Epitaxial growth of graphene directly on SiC substrate provides high-quality graphene in millimeter scale. Additionally, epitaxial growth of graphene enables to stack up to 100 layers of graphene making possible strong optical absorption. Here, we investigate the conductivity of multilayer epitaxial graphene in the vicinity of the Dirac point using THz time domain spectroscopy from 0.4 to 4 THz at temperature ranging from 4K to 300 K. We show that the properties of the quasi-neutral layers are well described by a Fermi level pinned at the Dirac point. We highlight that the dominant scattering mechanism close to the Dirac point is due to intrinsic mid-gap states whereas at higher energy (>8 meV), scatterings on short-range potential dominate. These mid-gap states introduced by intrinsic defects could be responsible for the pinning of the Fermi level at the Dirac point. Our results highlight the potential of multilayer epitaxial graphene for probing the properties of Dirac particles close to the Dirac point but also for applications of linear and nonlinear optics at THz frequencies.

10111-76, Session 18

Low-dimensional materials for optically-assisted microwave applications *(Invited Paper)*

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From latest nanotechnology advances, low-dimensional matter confinement delivered by nanostructuration or few-layer stacking offer new opportunities for ultimate light absorption performances. In this field, semiconducting 2D materials and photonic crystals have already demonstrated promising flexible optical properties from monoatomic to bulk structuration covering visible to IR spectral range. Today, these emerging materials such as Phosphorene, allow reconsideration of some physical effects such as photoconductivity. Indeed, its exploitation in integrated planar structures become beneficial in terms of efficient local contactless control with a high degree of tunability by optics in association with high dark resistivity, fast carrier dynamics, and sub-wavelength light coupling solutions compatibility.

Multiscale modeling and design tools implementing material anisotropic parameters from atomic configuration up to mesoscale, in complement with multiscale optical characterization in a large frequency bandwidth opens routes to new microwave signal processing functionalities such as switching, generation, amplification and emission over a large frequency bandwidth, that could not be achieved by full electronic solutions.

This paper will report on latest demonstrations of high performance photoconductive structures for high frequency applications and review state-of-the-art research work in this area, with a specific focus on latest demonstrations for airborne applications.

10111-77, Session 18

Current-injection terahertz lasing in a distributed-feedback dual-gate graphene-channel transistor *(Invited Paper)*

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[Invited] Optical and/or injection pumping of graphene can enable negative-dynamic conductivity in the terahertz (THz) spectral range, which may lead to new types of THz lasers. In the graphene structures with p-i-n junctions, the injected electrons and holes have relatively low energies compared with those in optical pumping, so that the effect of carrier cooling can be rather pronounced, providing a significant advantage of the injection pumping in realization of graphene THz lasers. We implement a forward-biased graphene structure with a lateral p-i-n junction in a distributed-feedback dual-gate graphene-channel field-effect transistor (DFB-DG-GFET) and experimentally observe a single mode emission at 5.2 THz at 100K. The single mode emission exhibits a non-monotonic threshold-like behavior with the highest intensity ~10 ?W, reflecting the carrier over-cooling effect under weak pumping. Spectral narrowing with increasing the carrier injection around the threshold was also observed. The emission spectra can fit to the Lorentzian curve with a Q factor of 170 (a linewidth of 30.6 GHz). The modal gain of the in-plane waveguided modes in the DFB-DG-GFET was analyzed by taking account of the DFB and the DG-stripline-induced in-plane Fabry-Perot hybridized cavity structures. The modal gain is estimated to be ~5 cm-1 at the lasing frequency, which fairly agrees with the experimental results. Although the results obtained are still preliminary level, the observed emission could be interpreted as world-first THz lasing in population-inverted graphene by carrier-injection.

10111-78, Session 19

Monolithic integrations of quantum cascade lasers *(Keynote Presentation)*

Kwok Keung Law, Naval Air Warfare Ctr. Weapons Div. (United States)

Quantum cascade lasers (QCLs) are increasingly incorporated into a variety of systems and sensing applications. Significant advances have been made recently in mid-wave infrared and long-wave infrared QCLs technologies. We will discuss in this presentation an update status on a portfolio of Navair's efforts on significantly improving QCLs' performance, affordability and reliability by means of monolithic integrations.

10111-79, Session 20

Control of the electromagnetic field in a cavity by an external perturbation *(Invited Paper)*

Michele Cotrufo, Technische Univ. Eindhoven (Netherlands); Ewold Verhagen, FOM Institute for Atomic and Molecular Physics (Netherlands); Andrea Fiore, Technische Univ. Eindhoven (Netherlands)

So far most efforts in the field of optomechanics have been focused on the coupling of mechanical motion to the frequency and loss rate of an optical mode (dispersive and dissipative coupling). Here we will discuss structures which are designed to maximize the variation of the spatial field distribution in response to mechanical displacement, and thereby of the coupling of quantum emitters to electromagnetic radiation. In photonic crystal waveguides patterned on double membranes, we theoretically and experimentally show that mechanical bending controls the effective potential and thereby directly affects the spatial and spectral properties of the resonant modes. We further discuss how the field redistribution can be maximized in a coupled-cavity system. We identify coupled optical modes which present large field response but zero dispersive coupling. In the presence of a quantum emitter, this translates into a change of the vacuum field seen by the emitter, and thereby into a mechanically-induced change of the emitter-photon interaction. This "vacuum field coupling" can be used to produce a tripartite emitter-photon-phonon interaction, enabling for example optically-controlled swapping of an excitation between the emitter and the phonon and the production of quantum states of the mechanics.

10111-80, Session 20

Fine control of collective nano-optomechanical architectures *(Invited Paper)*

Eduardo Gil-Santos, Biswarup Guha, Christophe Baker, Matthieu Labousse, Univ. Paris 7-Denis Diderot (France); Carmen Gomez Carbonell, Aristide Lemaître, Lab. de Photonique et de Nanostructures (France); Cristiano Ciuti, Giuseppe Leo, Ivan Favero, Univ. Paris 7-Denis Diderot (France)

After nano-optomechanics experiments that have ventured into the quantum regime, next developments in the field require improved control of the resonators themselves, be it for the reduction of dissipation or for the development of collective nano-optomechanical architectures. Nanoscale devices, with their extreme surface to volume ratio, have properties that strongly depend on surface interactions with the environment. Here we report on breakthroughs in the control of these interactions, for the benefits of nano-optomechanical applications.

At the single resonator level, we study two distinct surface control techniques for nanoscale Gallium Arsenide (GaAs) optomechanical disks. Both produce permanent results and lead to mitigate dissipation. The optical quality factor Q of processed resonators rises up to 6 million, a ten-fold improvement over prior state of the art. We analyze mechanisms at play in these techniques and discuss implications for nano-optomechanics.

At the level of collective architectures, we present a new technique to tune ensembles of resonators. Light resonantly injected into the optical mode of a resonator triggers an etching process when interacting with a fluid (gas or liquid), leading to a fine-tuning of the resonator. This tuning process, dubbed resonant photo-electrochemical etching, is naturally scalable and has allowed us to tune small ensembles of resonators. We demonstrate the versatility of the process and discuss its implementations.

Finally, we present a first application of these techniques: the resonant optical interaction of multiple nano-optomechanical systems, which has led us to observe collective behaviors involving several distant resonators.

10111-81, Session 20

Ultra-high throughput microfluidic optomechanical sensors *(Invited Paper)*

Kewen Han, Jeewon Suh, Alan Luo, Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)

Optical resonators have enabled the label-free measurement of nanoparticles suspended in liquids, down to the resolution of individual viruses and large molecules, but are only able to quantify optical properties (refractive index, scattering, fluorescence). Additionally, these sensors are fundamentally limited by the random diffusion of particles to the sensing region, and thus only measure a tiny fraction of the analyte. We have developed a microfluidic optomechanical resonator capable of sensing freely flowing nanoparticles using the action of phonons that are coupled to light. The phonon mode of the system casts a nearly perfect net for measuring density, viscoelasticity, and compressibility of the particles that flow through, without being limited by random diffusion. Information on the mechanical properties of the particles is encoded in the light scattered from the thermal fluctuations of the phonon mode. We have also developed a new electro-opto-mechanical method for improving the sensing speed achievable with this technique. We demonstrate real-time particle transit measurements as fast as 400 microseconds, without any post-processing. We discuss how this novel technique can be used for ultra-high throughput analysis of mechanical properties of biological particles in liquids, enabling a new form of flow cytometry.

10111-82, Session 20

Acoustic metamaterials and metasurfaces: a transformative approach for phononic insulators and energy harvesting *(Invited Paper)*

Badreddine Assouar, Shuibao Qi, Yong Li, Univ. de Lorraine (France) and Ctr. National de la Recherche Scientifique (France)

Recently, researches on the artificial sub-wavelength acoustic structures, called acoustic metamaterials and metasurfaces, have extended our knowledge beyond the current limits. By utilizing the intrinsic dynamic motions inside their unit cell structures and their specific designs, metamaterials and metasurfaces have shown various interesting wave phenomena, such as the wave cloaking, sound insulation, or even breaking reciprocity and time-reversal symmetry which were impossible to be realized previously. Above all, the metamaterials and metasurfaces can be designed to have the low-frequency stop band that can break-through the well-known mass-law, which is very important characteristic in various vibration and acoustic devices. In this presentation, we propose a transformative approach for phononic insulators and energy harvesting based on metamaterials and metasurfaces.

First, we will present some recent advances on low-frequency phononic and acoustic insulators based on metasurfaces. We will introduce a new concept of acoustic absorption based on the coiling-up space design which exhibits extreme acoustic properties. A new acoustic absorber operating at 125Hz with deep-subwavelength thickness (~lambda/230) acting as an "acoustic sink" is designed and its functionalities are discussed.

Second, as we are dealing with how to reduce or to absorb low-frequency sound/noise, we will explore a novel idea on the use in a positive manner these noises as a clean and renewable source of energy. We will present a first research about an acoustic energy harvester based on a planar metamaterial. A power density of 0.54μW/cm3 is obtained at a frequency of about 2kHz, as a result of an impinging acoustic pressure of 100dB. These proposed concepts should have broad applications since they can act simultaneously as both phononic insulator and energy harvester.

10111-83, Session 21

Quantum cascade detector at 4.3um wavelength in pixel array configuration

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Mid-infrared detection with semiconductor based pixel arrays attracted constant research interest over the past years. Remaining challenges for intersubband detectors are high device performance at elevated temperatures in combination with cost effective scalability to large pixel counts needed for applications in remote sensing and high resolution infrared imaging.

In this field, quantum cascade detectors may offer promising advantages such as photovoltaic room temperature operation at a designable operation wavelength with compatibility to stable material systems and growth technology.

We present a high performance InGaAs/InAIAs quantum cascade detector design suitable for pixel devices. The design is based on a vertical optical transition and resonant tunneling extraction. The 20 period active region is optimized for a high device resistance and thereby high detectivity up to room temperature. The pixels are fully compatible with standard processing technology and material growth to provide scalability to large pixel counts. An enhanced quantum cascade detector simulator is used for design optimization of the resistance and extraction efficiency while maintaining state of the art responsivity. The device is thermo-compression bonded to a custom read out integrated circuit with substrate bottom side illuminated pixels utilizing a metal grating coupling scheme. The operation wavelength is designed to align with the strong CO2 absorption around 4.3µm. A room temperature responsivity of 16mA/W and a detectivity of 5?10^7 cm√Hz/W was achieved in good agreement with our simulation results. Device packaging and thermo-electric cooling in an N2 purged 16 pin TO-8 housing has been investigated.

10111-84, Session 21

High photoresponse in room-temperature quantum cascade detectors based on a coupled-well design

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As intersubband photodetectors, quantum well infrared photodetectors have been demonstrated in wide wavelength range. Quantum-cascade detectors (QCDs) are one of a most promising photodetectors in terms of excellent Johnson noise limited detectivity resulting from zero-bias operation. In mid-infrared region, a high performance photodetector is required for many applications such as high-sensitive spectroscopic measurements by accessing fundamental absorption bands of molecules. However, QCDs have no photoconductive gain and as a result they exhibit a lower responsivity. A most advanced QCD operating at room temperature shows the responsivity of only 16.9 mA/W, in which a diagonal transition scheme has been applied at ?~8 ?m. Here we report a high photoresponse in room temperature operation in the QCD based on coupled-well design, operating in the response wavelength of 5.4 ?m. In the coupled-well design, the photoexcitation in the coupled quantum well takes place via vertical transition which leads to a large dipole moment. The photo-excited careers are transferred to the adjacent well via very fast resonant tunneling; then the careers are quickly relaxed down to lower levels due to LO-phonon depopulation. By optimizing the device configuration, a coupled-well QCD operated in room temperature demonstrates a high responsivity of ~120 mA/W which is nearly tenfold higher responsivity, compared with previously reported QCD. The room temperature operation in high responsivity QCDs offers a variety of applications ranging from spectroscopic measurement to other various fields as same as mercury cadmium telluride (MCT) detector.

10111-85, Session 21

Continuous-wave operation of MOVPE grown bi-functional quantum cascade laser/detectors

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Bi-functional active regions, capable of light generation and detection at the same wavelength, allow a straightforward implementation of the mid-infrared quantum cascade technology for integrated photonics. Different parts of the chip can be used for laser and for photodetectors. Potential applications are on-chip integrated sensors or lasers with integrated power monitoring capabilities. In the first bi-functional designs, wavelength matching was achieved using thicker barriers and reduced energy splitings between the extraction levels, but with the drawback of a reduced laser performance. The following introduction of the horizontal-vertical extraction scheme was a significant step towards high performance laser operation.

In this work, we combine our design experience with optimized, laterally overgrown waveguides and refined bandstructure modelling. The device was designed for emission at 8 ?m to show that wavelength matching can also be achieved at longer wavelengths, where it becomes increasingly difficult due to the smaller ratio between photon energy and LO-phonon energy. Graded interfaces were used in the bandstructure design to consider the behaviour of the MOVPE growth. In pulsed mode a threshold current density of 1.3 kA/cm 2 and a total wallplug efficiency of over 10% was achieved. In continuous-wave operation, the device emits 80mW output power in an episide-up configuration. A much higher performance can be expected after episide-down mounting on AIN substrates. In detector operation the device has a responsivity at the emission wavelength of about 20mA/W.

10111-86, Session 21

Beam steering in quantum cascade lasers with optical feedback *(Invited Paper)*

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Quantum cascade lasers are semiconductor lasers based on intersubband transitions that have developed rapidly and become the most suitable mid-infrared laser sources, due to their compactness, efficiency and high room temperature performances. High-power mid-infrared quantum cascade lasers are performant sources for optical countermeasures, including night vision blinding and missile out steering. However, some drawbacks arise with high power lasers that usually lead to a strong degradation of the beam quality. For instance, beam steering is known to be one of the

limiting factors inducing an irregular repartition of the optical power within the near-field beam profile. This phenomenon has already been observed in high power quantum cascade lasers before [1] and can be explained by four-wave mixing interaction among the existing transverse modes [2]. It dramatically degrades the far-field of the laser emission, and prevents its use for applications where high beam quality is required. In this work, we show for the first time that the use of a small amount of optical feedback reinjected into a high power quantum cascade laser emitting at 4.6 µm and with poor beam quality allows a total suppression of the beam steering effect without sacrificing the near-field profile.

References

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10111-87, Session 21

Real-time spectroscopy enabled by external cavity QCLs with MOEMS diffraction gratings

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External cavity quantum cascade lasers (EC QCLs) are very attractive semiconductor light sources for mid-infrared (MIR) fingerprint spectroscopy, providing high spectral brightness and tuning ranges of >35 % of the center wavelength, i.e. several hundreds of wavenumbers.

In this contribution, we focus on real-time MIR spectroscopy enabled by rapidly tunable EC QCLs. High speed spectral scanning in a Littrow-type resonator is realized by employing a resonantly driven micro-opto-electro-mechanical-systems (MOEMS) grating as wavelength selective element. Oscillating at a frequency of 1 kHz with a mechanical amplitude of up to 10°, the MOEMS grating is able to cover the whole spectral range provided by the QCL chip. Consequently, a full wavelength scan can be performed in just 500 µs. This MOEMS EC QCL paves the way for a wide range of real-time sensing applications, e.g. online process control in chemical and pharmaceutical industry as well as assessment of food quality.

In addition to the high spectral scanning frequency, the MOEMS approach also allows for a miniaturized and rugged design of the EC QC laser. We present an evaluation of this laser source with regard to spectral reproducibility of consecutive scans, amplitude noise, and spectral resolution in pulsed and cw operation. Furthermore, we report on spectroscopic measurements with such a MOEMS based EC QCL equipped with a broadband QCL chip. Both backscattering measurements for contactless identification of chemical substances as well as transmission measurements on liquids and gases will be presented, demonstrating the real-time capabilities of the light source in different scenarios.

10111-88, Session 21

Recent advances on long wave p on n HgCdTe infrared technology *(Invited Paper)*

Laurent Rubaldo, Rachid Taalat, Jocelyn Berthoz, Magalie Maillard, Nicolas Péré-Laperne, Alexandre Brunner, Pierre Guinedor, Loïc Dargent, Alain Manissadjian, Y. Reibel, Alexandre Kerlain, SOFRADIR (France)

SOFRADIR is the worldwide leader on the cooled IR detector market for high-performance space, military and security applications thanks to a well mastered Mercury Cadmium Telluride (MCT) technology, and recently thanks to the acquisition of III-V technology: InSb, InGaAs, and QWIP quantum detectors. As a result, strong and continuous development efforts are deployed to deliver cutting edge products with improved performances in terms of spatial and thermal resolution, dark current, quantum efficiency, low excess noise and high operability. The actual trend in quantum IR detector development is the design of very small pixel, with the higher achievable operating temperature whatever the spectral band. Maintain the detector operability and image quality at higher temperature moreover for long wavelength is a major issue. This paper presents the recent developments achieved at Sofradir to meet this challenge for MCT extrinsic p on n technology LW band with a cut-off wavelength of 9.3µm at 90K. State of the art performances will be presented in terms of dark current, operability and NETD temperature dependency, quantum efficiency, MTF, RFPN (Residual Fixe Pattern Noise) and its stability up to 100K will be shown.

10111-112, Session PWed

On the Einstein relation under size quantization in heterostructures semiconductor

Subhamoy Singha Roy, JIS College of Engineering (India)

In ultrathin films, the restriction of the motion of the carriers in the direction normal to the films leads to the quantum size effect allowing two-dimensional carrier transport parallel to the surface of the film. In this context I shall study the DMR in ultrathin films of III-V semiconductors.

10111-113, Session PWed

A compact mid-infrared dual-gas CH4/C2H6 sensor using a single interband cascade laser and custom electronics

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A compact mid-infrared (MIR) dual-gas sensor system was demonstrated for simultaneous detection of methane (CH4) and ethane (C2H6) using a single continuous-wave (CW) interband cascade laser (ICL) based on tunable laser absorption spectroscopy (TDLAS) and wavelength modulation spectroscopy (WMS). Ultracompact custom electronics were developed, including a laser current driver, a temperature controller and a lock-in amplifier. These custom electronics reduces the size and weight of the sensor system as compared with a previous version based on commercial electronics. A multipass gas cell with an effective optical length of 54.6 m was employed to enhance the absorption signal. A 3337 nm ICL was capable of targeting a C2H6 absorption line at 2996.88 cm-1 and a CH4 line at 2999.06 cm-1. Dual-gas detection was realized by scanning both the CH4 and C2H6 absorption lines. Based on an Allan deviation analysis, the 1 ? minimum detection limit (MDL) was 17.4 ppbv for CH4 and 2.4 ppbv for C2H6 with an integration time of 4.3 s. TDLAS based sensor measurements

for both indoor and outdoor concentration changes of CH4 and C2H6 were conducted. The reported single ICL based dual-gas sensor system has the advantages of reduced size and cost without influencing the mid-infrared sensor detection sensitivity, selectivity and reliability.

10111-114, Session PWed

A near-infrared gas sensor system based on tunable laser absorption spectroscopy and its application in CH4/C2H2 detection

Qixin He, Rice Univ. (United States); Chuantao Zheng, Rice Univ. (United States) and Jilin Univ. (China); Huifang Liu, Yiding Wang, Jilin Univ. (China); Frank K. Tittel, Rice Univ. (United States)

A near-infrared (NIR) dual-channel differential gas sensor system was experimentally demonstrated based on tunable laser absorption spectroscopy (TLAS) and wavelength modulation spectroscopy (WMS). The sensor consists of four modules, including distributed feedback (DFBs) lasers for the detection of targeted gases, a custom portable DFB driver compatible for butterfly-packaged DFB lasers, a 20cm-long open-reflective gas-sensing probe and a custom cost-effective lock-in amplifier for harmonic signal extraction. The optical and electrical modules were integrated to a standalone sensor system, which possesses advantages of easy operation, good stability, small volume and low cost. With different DFB lasers, the sensor system can be used to detect different gases. As an application, a DFB laser with an emission wavelength of 1.65 μm and another one with an emission wavelength of 1.53 μm were used to detect CH4 and C2H2, respectively. Standard CH4 and C2H2 samples were prepared and experiments were carried out to determine detection performance of these two gas species. The relation between the second harmonic amplitudes (2f) and gas concentration was obtained for the two gases by means of calibration. The limit of detection on CH4 was determined to be 29.52 ppm based on the Allan deviation with an averaging time of 1 s, and the relative detection error on C2H2 is < 5% within the concentration range of 200-10,000 ppm. The sensor system will be useful in industrial trace gas monitoring due to the use of low-loss optical fiber and the open-reflective gas-sensing probe.

10111-115, Session PWed

Filter-free measurements of black carbon absorption using photoacoustic spectroscopy

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Black carbon (BC) is a primary aerosol emitted directly from incomplete combustion processes such as fossil fuel and biomass burning. BC aerosol strongly absorbs solar radiation and warms the atmosphere. BC is considered as the third most powerful climate-forcing agent in the atmosphere after CO2 and CH4. BC has been also identified as the most harmful air pollutant in terms of its adverse impacts on human health.

Despite intensive efforts over the past decades, the uncertainties associated to BC radiative forcing are nowadays still larger than 70%, mainly related to actual measurement techniques that provide limited information to distinguish BC aerosol from other aerosols and to its optical properties. The most widely used methods are filter-based on-line aethalometry and off line thermal optical analysis. However all filter-based photometers suffer from non linearity due to the loading of the filter, which may lead to a large measurement bias.

In the present work, a photoacoustic (PA) spectrophone was developed for filter-free measurement of BC mass absorption coefficients (MAC) in the spectral region of ~440 nm using a blue diode laser. A minimum detected absorption coefficient (1?) of ~1.2 Mm?1 for BC was achieved. MAC of Eyjafjallajökull volcanic ash was then measured with a result in good agreement with the value obtained using a reference instrument. The PA experimental detail, the preliminary measurement results of BC, and the corresponding data analysis will be presented.

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10111-116, Session PWed

Monitoring of nitrous acid (HONO) by external-cavity quantum cascade laser-based off-beam quartz-enhanced photoacoustic spectroscopy (QEPAS)

Hongming Yi, Rabih Maamary, Univ. du Littoral Côte d'Opale (France); Xiaoming Gao, Anhui Institute of Optics and Fine Mechanics (China); Markus W. Sigrist, ETH Zürich (Switzerland); Eric Fertein, Weidong Chen, Univ. du Littoral Côte d'Opale (France)

Nitrous acid (HONO), as an important source of OH radicals, plays a central role in the atmospheric oxidation capacity that significantly affects the regional air quality and global climate change. Despite its importance and several decades of research, the sources and sinks of HONO as well as their formation mechanism in the atmosphere are still not completely defined and understood. This is due to the difficulty in measuring this chemically reactive short-lived species, which requires: (1) ultrahigh sensitivity with high measurement precision (typical environmental HONO concentration : 2-5 ppbv); (2) fast time response and high spatial resolution (its atmospheric lifetime : 10-20 minutes); (3) residence time as short as possible to ensure high measurement accuracy.

In this presentation, we report on the high sensitivity and high selectivity measurement of HONO by off-beam quartz-enhanced photoacoustic spectroscopy (QEPAS) in a very small gas sample volume (of ~40 mm3) resulting in a ultrashort residence time of less than 10 ms (compared to ~7 min for a conventional 210 m multipass cell or ~10 min for currently used chemical analytical instruments). A minimum detection limit of 66 ppbv (1?) HONO was achieved at 70 mbar using a laser output power of 50 mW and 1 s integration time. This MDL was down to 7 ppbv at the optimal integration time of 150 s [Appl. Phys. Lett. 106 (2015) 101109].

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10111-117, Session PWed

Detection of prostate specific antigen using silicon photonic crystal nanocavity resonator

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In this paper we explain photonic crystal (PhC) based nanocavity biosensor for early stage medical diagnosis. We reported on the highly sensitive detection of real biomarker of prostate specific antigen (PSA), those used in medical diagnosis. The purpose of this study is to confirm the detection

of the PSA marker considerably lower than 1 ng /mL. PhC resonators were fabricated by using electron beam lithography and dry etching. The unique point of our work is to use the silicon-binding protein (designated as Si-tag), which anchoring with sensor surface and immobilize the bioreceptors (protein G). The protein G which bonds to many kinds of mammalian antibodies only by mixing the antibody solution and has higher binding energy with antigen. The label-free detection of antigen can be achieved by using Si-tag and protein G. Firstly, by using the micropipette, the solution of Si-tagged protein G was poured on the sample surface and wait for 10 min. Secondly, the solution of anti-PSA (IgG2a: immunoglobulin G2a) is poured and wait for 10 min, next, the solution of PSA with certain concentration is poured for 20 min and measured the resonance wavelength shift. After that the sample is washed by buffer solution (Tris–HCl) to repeat the measurement process at different concentrations. The different concentrations of PSA solutions are measured from lower to higher concentration. By optimizing the immobilization of the antibody and injecting surfactants, we detected 0.5 ng/mL. We also confirm the reproducible even measurements were carried out after two weeks.

10111-118, Session PWed

A low-temperature photoluminescence study of GaAs1-xNx/GaAs multiple quantum-wells

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Coherently strained InGaAsN/GaAs multiple quantum wells (MQWs) were employed fabricating photo-pumped vertical cavity surface emitting lasers and quantum well edge emitting layers operating at 1.33 ?m. But, addition of Indium causes surface segregation and diffusion that degrade the device performance. Engineering crystal growth, a good quality of GaAs1-xNx/GaAs MQWs, under tensile strain, remained less studied even at materials levels could be explored.

We report here the growth of GaAs1-xNx/GaAs MQWs through solid source molecular beam epitaxy by varying nitrogen background pressure and investigate its structural and optical quality. High resolution X-ray diffraction revealed that the five-period GaAs0.982N0.018/GaAs and GaAs0.978N0.022/GaAs MQWs grown at background pressures of 4 ? 10?6 and 5 ? 10?6 Torr exhibited interface roughness of 3.23 and 2.02%, respectively. A linear relationship between the full width at half maximum (FWHM) of the satellite peaks and satellite peak order was established. Photoluminescence measurements recorded at 19 K exhibited a high intensity in GaAsN0.022/GaAs MQWs as compared to the former because of decrease in surface recombination at an increased nitrogen composition. An asymmetric nature at low energy regime in PL spectrum was observed, attributed to the potential fluctuations around the conduction band edge of GaAsN caused by N-related states or cluster of N atoms. Rapid thermal annealing at 700?C resulted in a 100-fold improvement in PL intensity with evidently reduced FWHM. A low interface roughness and high photoluminescence intensity leads to a good crystal interface observed for the GaAs0.0978N0.022/GaAs MQWs. Thus, these MQWs could be employed in optoelectronic device application.

10111-119, Session PWed

Fabrication, characterisation, and epitaxial optimisation of MOVPE-grown resonant tunnelling diode THz emitters

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Resonant tunnelling diodes (RTDs) are a favorite candidate for future wireless communications in the THz region, offering compact, room-temperature and dust-proof operation with Gb/s transfer rates. We employ the InGaAs/AlAs/InP material system, offering advantages due to high electron mobility, suitable band-offsets, and low resistance contacts.

We describe an RTD emitter operating at 353GHz, radiating in this atmospheric transmittance window through a slot antenna. The fabrication scheme uses a dual-pass technique to achieve reproducible, very low resistivity, ohmic contacts, followed by accurate control of the etched device area. The top contact connects the device via the means of an air bridge.

We then proceed to model ways to increase the resonator efficiency, in turn improving the radiative efficiency, by changing the epitaxial design. The optimization takes into account the accumulated stress limitations and realities of reactor growth.

Due to the absence of useful in-situ monitoring in commercially-scalable metal-organic vapor phase epitaxy (MOVPE), we have developed a robust non-destructive epitaxial characterisation scheme to verify the quality of these mechanically shallow and atomically thin devices. A dummy copy of the active region element is grown to assist with low temperature photoluminescence spectroscopy (LTPL) characterisation. The resulting linewidths limits the number of possible solutions of quantum well (QW) width and depth pairs. In addition, the doping levels can be estimated with a sufficient degree of accuracy by measuring the Moss-Burstein shift of the bulk material. This analysis can then be combined with high resolution X-ray diffractometry (HRXRD) to increase its accuracy.

10111-120, Session PWed

High contrast grating VCSELs for sensing applications

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High Contrast Gratings (HCGs) become an attractive alternative for Distributed Bragg Reflectors (DBRs) used as high reflecting mirrors for VCSELs. In our analysis we implement HCG or monolithic HCG as a top mirror of the 1650 nm InP-based VCSEL intended for use as a methane sensing device. Its unique feature is related to the fact that light taking part in the resonance can be accessed without needing to open the laser cavity due to the slow light phenomenon which occurs in HCG. Particular designs of HCGs allow to concentrate significant part of the mode between the HCG stripes. In such constructions the presence of the substance in the vicinity of the HCG which interacts with light resonating in the laser will change its emission properties. This makes possible sensing either absorption or change to the refractive index based on the emitted light by the laser. We present a numerical analysis of 1650 nm InP-based HCG VCSELs based on fully vectorial optical model. We found optimal parameters of HCGs to detect absorption and refractive index variations in the vicinity of the gratings, based on changes in emitted power and resonant wavelength. Additionally, we consider HCG VCSEL constructions which allow for broad wavelength tuning by the change of the refractive index of substance surrounding HCG. Such substance can be a liquid crystal allowing for modifications of its optical properties by electrical field.

10111-121, Session PWed

RGO-based nanocomposites with sulphide compounds and their chemical properties

Woo-Gwang Jung, Fatima Tuz Johra, Kookmin Univ. (Korea, Republic of)

Graphene, the one-atom thick two-dimensional sp2 carbon arrangement has been considered a promising material due to its ultrahigh surface area, excellent electric conductivity and chemical and physical stability. A lot of researches have been made on graphene or related materials. Chemical approaches to the large-scale production of graphene have been realized, and the production of RGO (Reduced Graphene Oxide) in quantity has considerably advanced the development of applications for RGO in photocatalysis, capacitive deionization, and solar cells.

In the present study, the improvement of synthesis process of RGO was made in terms of temperature, time and safety, as well as introduction of RGO based nanocomposite material. RGO was synthesized by the two step process which is very simple and easy; the conversion of graphite to GO by oxidation and then reduction of the GO to RGO by hydrothermal treatment. The synthesized RGO was combined with nano-size CdS and CuS compounds. The photocatalytic performance of the composite were investigated with the reduction of Cr(VI) for the RGO-CdS nanocomposite. This results may give an insight for the possibility of RGO-CdS in application for the remover of Cr(VI) ion. The hydrothermally synthesized RGO-CuS contains nanoplate shaped CuS with hexagonal structure. The adsorption property of methylene blue of RGO-CuS nanoparticles were compared with bare CuS. Also, it is confirmed that RGO-CuS nanocomposite can be used for the adsorbent of methylene blue.

10111-122, Session PWed

The study of quantum spectral imaging

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At the beginning of 2001, professor Siwen Bi at home and abroad for the first time put forward the new subject orientation of Quantum Remote sensing. Based on the theory of Quantum Remote Sensing and information mechanism, a new concept of quantum spectral imaging was proposed in the August 2006. In the 10 years, the research of quantum spectral imaging has made a breakthrough progress and the results of the stage.

This paper first outlines the background and research status of quantum spectral imaging spectral imaging, and then introduces the concepts and research methods of quantum spectral imaging, contrast and advantages of quantum spectral imaging and spectral imaging. This paper expounds the basic theory of quantum spectra, focuses on the experimental study of quantum spectral imaging and the study of quantum spectral imaging technology. Finally, the significance and application prospect of quantum spectral imaging are described.

10111-89, Session 22

Quantum interference in monolithic nanophotonics *(Keynote Presentation)*

Ryan P. Marchildon, Amr S. Helmy, Univ. of Toronto (Canada)

In this talk, monolithic photonics architectures that enable deterministic splitting of entangled states of light will be discussed. In addition, quantum state engineering using the same architectures will be presented exhibiting characteristics that are unique to integrated architectures.

10111-90, Session 23

Multi-user quantum key distribution with a semiconductor source of entangled photon pairs *(Invited Paper)*

Sara Ducci, Claire Autebert, Univ. Paris 7-Denis Diderot (France); Julien Trapateau, Adeline Orieux, Lab. Traitement et Communication de l'Information (France) and Ctr. National de la Recherche Scientifique (France); Aristide Lemaître, Carmen Gomez Carbonell, Ctr. de Nanosciences et de Nanotechnologies (France) and Ctr. National de la Recherche Scientifique (France); Eleni Diamanti, Isabelle Zaquine, Lab. Traitement et Communication de l'Information (France) and Ctr. National de la Recherche Scientifique (France)

In view of real world applications of quantum information technologies, the combination of miniature quantum resources with existing fibre networks is a crucial issue. Among such resources, on-chip entangled photon sources play a central role for applications spanning quantum communications, computing and metrology. Here, we use a semiconductor source of entangled photons operating at room temperature in conjunction with standard telecom components to demonstrate multi-user quantum key distribution, a core protocol for securing communications in quantum networks. The source consists of an AlGaAs chip emitting polarization entangled photon pairs over a large bandwidth in the main telecom band around 1550 nm without the use of any off-chip compensation or interferometric scheme; the photon pairs are directly launched into a dense wavelength division multiplexer (DWDM) and secret keys are distributed between several pairs of users communicating through different channels. We achieve a visibility measured after the DWDM of 87% and show long-distance key distribution using a 50-km standard telecom fibre link between two network users. These results illustrate a promising route to practical, resource-efficient implementations adapted to quantum network infrastructures.

10111-91, Session 23

High absorption efficiency and polarization-insensitivity in superconducting-nanowire single-photon detectors *(Invited Paper)*

Luca Redaelli, CEA-INAC (France); Gabriele Bulgarini, Sergiy Dobrovolskiy, Sander Dorenbos, Single Quantum (Netherlands); Anna Mukhtarova, CEA-INAC (France); Val Zwiller, KTH Royal Institute of Technology (Sweden) and Technische Univ. Delft (Netherlands); Eva Monroy, Jean-Michel Gérard, CEA-INAC (France)

Highly efficient single-photon detectors are essential for many fundamental quantum optics experiments, but also for applications such as quantum cryptography, satellite communication, and integrated-circuit testing. Superconducting-nanowire single photon detectors (SNSPDs) have demonstrated detection efficiencies in excess of 90% in the near infrared, outperforming avalanche photodiodes in this wavelength range.

The SNSPD performance depends on the light absorption efficiency in the ultrathin (3-8 nm) superconducting nanowire. In this work, we will discuss two main approaches to boost light absorption, namely coupling

the nanowire to the evanescent field propagating in a waveguide, and enclosing the nanowire in an optical cavity [1]. The former method allows absorption efficiencies close to unity, which are nearly independent from the polarization of light and extend on a broad wavelength range. Waveguide-coupled SNSPDs are widely used for integrated-optics experiments, but the difficulty to efficiently couple the light into the waveguide limits their use in other fields.

On the other hand, enhancing absorption by means of an optical cavity is the method of choice for stand-alone detectors. However, this geometry is intrinsically very sensitive to the polarization of light. The narrower the nanowire, the higher the polarization sensitivity. To overcome this issue, we propose some innovative cavity designs which make use of high-index (n >2) dielectrics [2]. With this technique, highly-efficient polarization-insensitive devices can be easily implemented. Experimental demonstrators based on this approach will be presented.

[1] L. Redaelli et al., Supercond. Sci. Technol. 29, 065016 (2016).

[2] L. Redaelli et al., arXiv:1607.01273 [physics.ins-det] (2016).

10111-92, Session 23

SUPERTWIN: towards 100kpixel CMOS quantum image sensors for quantum optics applications *(Invited Paper)*

Leonardo Gasparini, Fondazione Bruno Kessler (Italy); Bänz Bessire, Institut für Angewandte Physik, Univ. Bern. (Switzerland); Manuel Unternährer, André Stefanov, Institut für Angewandte Physik, Univ. Bern (Switzerland); Dmitri L. Boiko, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Matteo Perenzoni Jr., David Stoppa, Fondazione Bruno Kessler (Italy)

Quantum imaging uses entangled photons to overcome the limits of a classical-light apparatus in terms of image quality, beating the standard shot-noise limit, and exceeding the Abbe diffraction limit for resolution.

In today experiments, the spatial properties of entangled photons are recorded by means of complex and slow setups that include either the scanning of single-pixel single-photon detectors, such as Photo-Multiplier Tubes or avalanche photodiodes, or the use of low frame rate intensified CCD cameras.

CMOS arrays of Single Photon Avalanche Diodes (SPAD) represent a relatively recent technology that may lead to simpler setups (no need for scanning stages) and faster acquisition. They are spatially- and time-resolved single-photon detectors, i.e. they can provide the position within the array and the time of arrival of every detected photon with <100 ps resolution.

SUPERTWIN is a European H2020 project aiming at developing the technological building blocks (emitter, detector and system) for a new, all solid-state quantum microscope system exploiting entangled photons to overcome the Rayleigh limit, targeting a resolution of 40nm.

This work provides the preliminary results of measurement of the 2nd order cross-correlation function relative to a flux of entangled photons pairs acquired with a fully digital 8?16 pixel SPAD array in CMOS technology. The limitations for application in quantum optics of the employed architecture and of other solutions in the literature will be analyzed, with particular emphasis on crosstalk. Then, the specifications for a dedicated detector will be given, paving the way for future implementations of 100kpixel Quantum Image Sensors.

10111-93, Session 23

Emission of nonclassical radiation by a dc-biased Josephson junction *(Invited Paper)*

Fabien Portier, Commissariat à l'Energie Atomique (France); Chloe Rolland, Marc Westig, Olivier Parlavecchio, Patrice Roche, Yuri Mukharsky, Ambroise Peugeot, Denis Vion, Max Hofheinz, Carles Altimiras, Philippe Joyez, Daniel Esteve, Commissariat à l'Énergie Atomique (France)

Alternating currents driven through a classical conductor are the simplest source of microwave radiation. In the case of a simply dc biased quantum conductor, quantum fluctuations of the current due to the probabilistic character of charge transfer are already enough to emit radiation in the embedding circuit. Whereas it has long been known that for a classical current, the emitted radiation can be described as a coherent state, much less is known when the source of the emitted radiation is the electrical current through a quantum conductor. What is the connection between the quantum properties of the charge carriers and those of the emitted radiation? Can one take advantage of quantum electric transport to produce non classical radiation? For a Josephson junction, this emission can be understood through a simple picture: at bias voltage V smaller than the gap voltage, quasiparticle excitations cannot take away energy. Therefore, a dc current flows through the junction only if the entire energy 2eV of tunneling Cooper pairs is transferred into the environment. In this talk I will show that one can use a dc biased Josephson junction as a simple and bright source of nonclassical radiation through two examples: first when coupled to two resonators of different frequencies, upon proper biasing, the radiation is emitted as photon pairs into the two resonators, violating a Cauchy-Schwartz inequality obeyed by classical states. Then I will show that the photons emitted by a junction coupled to a high impedance mode are strongly antibunched.

10111-94, Session 23

Highly efficient readout integrated circuit for dense arrays of SPAD detectors in time-correlated measurements *(Invited Paper)*

Alessandro Cominelli, Giulia Acconcia, Pietro Peronio, Ivan Rech, Politecnico di Milano (Italy); Massimo Ghioni, Politecnico di Milano (Italy) and Micro Photon Devices S.r.l. (Italy)

In the last years, Time Correlated Single Photon Counting (TCSPC) has become the technique of choice in fluorescence lifetime measurements, given its remarkable sensitivity, accuracy and timing resolution. Nevertheless, a major drawback of this technique lies in the relatively long acquisition time. In order to overcome this issue, many multichannel systems have been proposed in literature, but the presence of many independent acquisition chains gives rise in principle to a huge data rate at the output, which cannot be processed in real time by a PC.

Typically adopted solutions involve a limitation of the maximum detection frequency of each channel, so the measurement speed of currently available systems has not increased accordingly with the number of acquisition chains and is still limited well below the saturation of the transfer rate towards the elaboration unit.

We present a completely different approach: starting from the maximum manageable data rate imposed by the transfer towards the PC, a proper number of high-performance external channels has been chosen to be shared among a much larger number of Single Photon Avalanche Diode (SPAD) detectors. Then, at each excitation period a dynamic routing mechanism performs a selection among the whole set of detectors carrying a valid signal and routes them towards the external channels. The selection logic relies on a pixelated architecture and on 3D-stacking techniques to connect each SPAD to its dedicated electronic, leading to a minimization of the number of interconnections crossing the system, which is one of the main issues in high-density arrays.

10111-95, Session 23

High-dimensional quantum cloning and cryptography using structured light *(Invited Paper)*

Robert Fickler, Frédéric Bouchard, Alicia Sit, Jérémie Gagnon-Bischoff, Hugo Larocque, Fatimah Alsaiari, Zohreh Hirbodvash, Yingwen Zhang, Univ. of Ottawa (Canada); Robert W. Boyd, Univ. of Ottawa (Canada) and Institute of Optics, Univ. of Rochester (United States); Ebrahim Karimi, Univ. of Ottawa (Canada) and Institute for Advanced Studies in Basic Sciences (Iran, Islamic Republic of)

Light with a complex amplitude structure invokes interesting fundamental properties, which in turn enables novel applications in classical and quantum optical experiments. One feature, namely a twisted phase front and its orbital angular momentum, attracted a lot of attention due its broad range of applications. In the quantum domain, structured photons are highly beneficial since they serve as a physical realizations of high-dimensional states, which allow an enlarged information content per single carrier and are known to have a better noise resistance in quantum cryptography applications.

At first I will present a high-dimensional optimal cloning scheme, which is realized in a linear optical systems by means of the symmetrisation method, a method involving the two-photon interference effect at a beam splitter. We used this technique to realize the first experimental demonstration of high-dimensional quantum cloning up to dimension 7. We characterize our cloning machine by performing full quantum state tomography of high-dimensional cloned states and demonstrate a cloning attack on a high-dimensional quantum cryptography protocol. The latter nicely shows the benefits of using high-dimensional states for secure communication.

In another set of experiments we get a step closer to real world applications and investigate long distance quantum cryptography using structured light. Here we investigate quantum cryptography over an approx. 280m long intra-city link and study the influence of turbulence on achievable key rates. We also test the long distance distribution of structured photons with the help of recently developed vortex fibers and show their applicability in quantum informational tasks.

10111-97, Session 24

Recent progress in the development of quantum-dot-based devices in NIR and THz ranges *(Invited Paper)*

Edik U. Rafailov, Ksenia A. Fedorova, Andrei Gorodetsky, Natalia Bazieva, Aston Univ. (United Kingdom)

In recent years, there has been a growing interest in the development of compact and low-cost, versatile, broadly tunable CW and ultrashort pulse laser sources generating light across the near-infrared and visible spectral ranges. In this talk we are presenting the recent progress on the development of novel compact quantum dot based laser sources generating light across broad spectral ranges in CW and ultrashort pulse regimes. We will present our recent results on the development on an ultra-compact, room-temperature, CW broadly-tunable dual-wavelength InAs/GaAs QD external-cavity diode laser in the spectral region between 1150 nm and 1301 nm. This laser source generating two modes with tunable difference-frequency (300 GHz - 30 THz) and maximum output power exceeded 250 mW has a great potential to replace commonly used bulky lasers for THz generation in photomixer devices.

We also will review our work on development QD-based THz antennae, capable of being pumped at very high optical intensities of higher than 1 W optical mean power, i.e. about 50 times higher than the conventional LT-grown material based antennae. QD-based antennae samples show no saturation in THz generation for all pump powers up to 1.2 W. Generated THz power is superlinearly proportional to laser pump power. The generated THz spectrum deepens on antennae design and can cover from 150 GHz up to 1.5 THz.

10111-98, Session 24

Dynamic control of CQED effects in switched optical microcavities *(Invited Paper)*

Jean-Michel Gérard, Emanuel Peinke, T. Sattler, Joël Bleuse, Julien Claudon, Commissariat à l'Énergie Atomique (France); Gaston Hornecker, Alexia Auffèves, Institut NÉEL (France); Emre Yüce, Henri Thyrrestrup, Willem L. Vos, Univ. Twente (Netherlands)

It is well known since the late 80's that the optical modes and optical response of semiconductor microcavities can be changed in a transient and reversible way through a modification of the refractive index of the semiconductor matrix. We show that cavity switching -initially developed in view of all-optical data processing and computing- can also be used to tailor the spontaneous emission of embedded emitters, by enabling a dynamic control of the emitter-cavity mode detuning [1].

Recent theoretical advances show that single photons with a tailored time-envelope can be generated by a single quantum dot (QD) in a microcavity with a high efficiency and fidelity, by adjusting in real-time the magnitude of the Purcell effect [2]. This is noticeably the case for Gaussian envelopes and time reversed-exponential envelopes, both important resources for photonic quantum information processing. Kerr-switching on the sub-ps time scale [3] could also be used to control Rabi oscillations in strongly-coupled semiconductor systems.

We also report recent switching experiments performed on micropillars containing collections of QDs. We observe large switching amplitudes (by as much as 20 linewidth), as well as differential switching of the pillar modes [4], using ultrafast optical carrier injection. Furthermore, cavity switching is used for the first time to generate ultrashort (down to 4ps!) and incoherent pulses of spontaneous emission.

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[3] G. Ctistis et al, APL 98,161114(2011); E. Yüce et al, OL 38,374(2013)

[4]H. Thyrrestrup et al, APL 105,111115(2014)

10111-99, Session 24

Integrated single-photon sources with colloidal semiconductor nanocrystals *(Invited Paper)*

Alberto Bramati, Lab. Kastler Brossel, Univ. Pierre et Marie Curie (France)

In this talk I will present our recent results on efficient room temperature single photon emitters based on core/shell colloidal semiconductor nanocrystals. By using asymmetric core/shell nanoparticles with a spherical CdSe core surrounded by a rod-like CdS shell (dots-in rods), blinking effects, multi-excitonic emission and polarization of the emitted photons can be separately controlled by tuning shell dimensions [1]. This allows an unprecedented capability in radiative channels engineering, making dot-in-rods "state of the art" blinking-free sources of polarized single photons on-demand.

In the last part of the talk I will discuss the different strategies we are pursuing to develop hybrid photonic devices by coupling single nanocrystals with various photonic structures like optical nanofibers, deep parabolic mirrors [2], liquid crystals [3] and semiconductor nanowires [4].

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[2] V. Salakhutdinov, M. Sondermann, L. Carbone, E. Giacobino, A. Bramati, G. Leuchs, Optical trapping of nanoparticles by full solid-angle focusing , Arxiv:1511.09042

[3] L. Pelliser, M. Manceau, C. Lethiec, D. Coursault, S. Vezzoli, G. Leménager, L. Coolen, M. DeVittorio, F. Pisanello, L. Carbone, A. Maître, A. Bramati, E. Lacaze, Alignement of Rod-Shaped Single Photon Emitters driven by Line Defects in Liquid Crystals, Adv. Funct. Mat. 25, 1719 (2015)

[4] W. Geng, M. Manceau, N. Rahbany, V. Sallet, M. De Vittorio, L. Carbone, Q. Glorieux, A. Bramati, C. Couteau, Localised excitation of a single photon source by a nanowaveguide, Scientific Reports, 6, 19721 (2016)

10111-100, Session 24

Intraband transition in self-doped narrow band gap colloidal quantum dots

Bertille Martinez, Institut des NanoSciences de Paris, Univ. Pierre et Marie Curie (France); Clement Livache, Institut des NanoSciences de Paris, Univ. Pierre et Marie Curie (France) and Ctr. National de la Recherche Scientifique (France); Adrien Robin, ESPCI (France); Herve cruguel, Sebastien Royer, cnrs (France); xiang zhen xu, cnrs (France) and ESPCI (France); Herve Aubin, cnrs (France); Sandrine Ithurria, Ecole Supérieure de Physique et de Chimie Industrielles de la Ville de Paris (France); Emmanuel Lhuillier, Institut des NanoSciences de Paris, Univ. Pierre et Marie Curie (France) and Ctr. National de la Recherche Scientifique (France)

Colloidal nanocrystals offer an alternative path to access to low dimensional object compared to epitaxially grown semiconductor. Over the past two decades most of the efforts have been focused on the growth of wide band gap material with optical properties in the visible range of wavelength. More recently the synthesis of mercury chalcogenides compounds have led to infrared optical signal, first in the mid infrared and now reaching the THz range.

In particular HgSe and HgS are self-doped nanocrystals which present and absorption signal resulting from intraband transition within the conduction band. Nanocrystals were suffering for long from a bad reputation because of their far less mature transport properties. Indeed transport in nanocrystal solid result from a hopping process associated with a low mobility. As a result the diffusion length remains one order of magnitude shorter than the absorption depth. Increasing the inter nanoparticle coupling is thus mandatory. Here we demonstrate a new colloidal synthesis of HgSe nanocrystals with tunable optical features from 3 to 20 µm and with surface chemistry which lead to very high carrier mobility up to 100cm2.V-1s-1. This is really a key step toward the use of colloidal nanocrystal for infrared photodetection. We also address two critical points for the future integration of such material which are the scale up of the material synthesis and its clean room processability for the design of pixel array.

10111-96, Session 25

Design challenges and potential mitigation approaches for orbital angular momentum-multiplexed free-space links *(Keynote Presentation)*

Alan E. Willner, The Univ. of Southern California (United States)

Over the past few years, progress has been made in understanding the potential advantages and systems limitations of using multiplexed orbital angular momentum (OAM) beams for free-space optical links. This paper will discuss several technical challenges and limitations related to the future implementation of OAM-based systems, such as atmospheric turbulence effects, free-space beam divergence, and obstructions. This paper will also describe some of the potential mitigation approaches to these challenges as well as design guidelines for transmission systems.

10111-101, Session 26

Properties of novel metamorphic III-V materials with ultra-low bandgaps *(Invited Paper)*

Sergey Suchalkin, Gregory Belenky, Leon Shterengas, Boris Laykhtman, Gela Kipshidze, Maxim Ermolaev, Stony Brook Univ. (United States); Dmitry Smirnov, Jonathan Ludwig, Seongphill Moon, David Graf, Florida State Univ. (United States); Stefan P. Svensson, Wendy L. Sarney, U.S. Army Research Lab. (United States)

We present magnetooptical and transport properties of metamorphic periodic structures containing InAsSb layers with controllable modulated Sb composition [1]. The modulation period is determined by the thicknesses of the strain compensated InAsSbx/InAsSby pairs grown on a virtual AlGaInSb substrate with a lattice constant of 6.25 A. We demonstrate that the bandgap energy of ordered InAsSb0.3/InAsSb0.75 alloy varies from 100mev to a few meV as a result of the well-regulated variation of the modulation period from ?3 to ?7.5 nm. The material effective masses and the specific character of the energy spectra will be discussed.

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10111-102, Session 26

Efficient extraction of photons from a single defect in hBN using a nanofiber

Andreas W. Schell, Kyoto Univ. (Japan); Trong Toan Tran, Igor Aharonovich, Univ. of Technology, Sydney (Australia); Hideaki Takashima, Shigeki Takeuchi, Kyoto Univ. (Japan)

Efficient extraction of photons from quantum emitters is an important prerequisite for the use of such emitters in quantum optical applications as single photons sources or sensors. One way to achieve this is by coupling to a suited photonics structure, which guides away the emitter light. Here, we show the coupling of a single defect in hexagonal boron nitride (hBN) to a tapered optical fiber via a nanomanipulation technique. Defects in hBN are capable of emitting single photons at room temperature while being photostable at the same time – two properties that make them ideal candidates for integration in single photon sources. The high control the manipulation technique provides avoids covering the whole nanofiber with emitters. We characterize the coupled system in terms of achievable count rates, saturation intensity, and spectral properties. Antibunching measurements are used to proof the single emitter nature of the defect. Our results pave the way for integration of single defects in hBN into photonic structure and their use as single photon sources in quantum optical applications such as quantum crypthography.

10111-103, Session 26

Electric and magnetic sensing with NV ensembles in diamonds

Sarvagya Sharma, Univ. of Illinois at Urbana-Champaign (United States); David C. Hovde, Southwest Sciences, Inc. (United States); Fahad Alghannam, Institute for Quantum Science and Engineering (IQSE) and Department of Physics and Astronomy (United States) and The National Center for Applied Physics, KACST, P.O.Box 6086, Riyadh 11442 (Saudi Arabia); Doug H. Beck, Univ. of Illinois at Urbana-Champaign (United States)

We report measurements of optically detected magnetic resonance spectra of ensembles of negatively charged nitrogen-vacancy (NV-) centers in diamonds in the presence of electromagnetic fields. To reduce inhomogeneous broadening, the spectra are acquired from a region of 20 cubic microns using a confocal setup. A microwave loop is used to drive magnetic transitions within the ground state of the NV center. The Stark shift from transverse electric fields is enhanced at avoided crossings between hyperfine spectra which occur near longitudinal magnetic fields of 0 and +/- 100 uT. A spatial map of the electric field between the lithographically printed electrodes has been made and vector information is extracted from NV axes oriented along the four different crystallographic directions of the diamond. This apparatus is also used in the absence of electromagnetic fields to measure strain inside the crystal lattice which shifts the energy levels like an external electric field. For cryogenic measurements, the diamond is mounted in a cryostat and electric field sensitivity is observed in optically pumped anti-holes where spin non-preserving transitions are seen under electric fields. Electromagnetically Induced Transparency(EIT) is also demonstrated as a method to study to the ground state energy structure of NV centers. This method provides an all-optical approach to measure electric and magnetic fields.

10111-106, Session 27

Optical parametric sources for gas sensing applications *(Invited Paper)*

Antoine Godard, Guillaume Aoust, Julie Armougom, ONERA (France); Erwan Cadiou, ONERA (France) and Ctr. National d'Études Spatiales (France); Delphine Descloux, ONERA (France); Guillaume Walter, ONERA - the French Aerospace Lab (France); Jean-Baptiste Dherbecourt, Guillaume Gorju, Jean-Michel Melkonian, Myriam Raybaut, Michel Lefebvre, ONERA (France)

Laser absorption spectroscopy is a powerful tool for trace gas detection. Depending on the application, the required laser spectral range can be either 1.6–2.2 ?m for spaceborne monitoring of greenhouse gases, 3–5 ?m for volatile organic compounds sensing, or 6–14 ?m for hazardous chemicals detection.

Various optical sources (solid state lasers, fiber lasers, semiconductor lasers or optical parametric devices) have demonstrated their high potentiality to cover the infrared range of interest; nonetheless, delivering a narrow linewidth radiation with a high wavelength agility remains challenging.

In this talk, we will present the developments that have been carried out in our laboratory for that purpose. Most of them have been dedicated to novel optical parametric sources and their integration in gas sensing instruments. In particular, we have introduced the nested cavity optical parametric oscillator (NesCOPO) scheme that enables to deliver a single frequency tunable emission with a much simpler and more compact device than usual narrow-linewidth OPOs. The NesCOPO device was successfully demonstrated in the microsecond to nanosecond regime and in spectral ranges from short- to long-wave infrared. Its high potential was demonstrated for multiple-gas sensing, either for point measurements or standoff gas detection using lidar instruments. For long range applications, the compact NesCOPO is implemented in a master-oscillator power-amplifier architecture. For local sensing, activities are also carried out to develop compact quartz-enhanced photoacoustic spectroscopy sensors. We will also present our recent advances on rapidly tunable picosecond OPOs based on aperiodic quasi-phase matching and their application to gas detection.

10111-107, Session 27

Biomedical application of optical fibre sensors *(Invited Paper)*

Serhiy A. Korposh, The Univ. of Nottingham (United Kingdom); Seung-Woo Lee, Univ. of Kitakyushu (Japan); Stephen W. James, Cranfield Univ. (United Kingdom); Ralph Tatam, Cranfiled University (United Kingdom); Stephen P. Morgan, The Univ. of Nottingham (United Kingdom) and Univ. of Kitakyushu (Japan)

Optical techniques are considered as powerful tools for the development of chemical and biological sensors, covering a wide range of applications. Sensing techniques based upon the use of optical fibre devices to probe the optical characteristics of nanomaterials that exhibit changes in their optical properties upon exposure to targeted chemical species are particularly attractive, due to their potential high sensitivity, selectivity, the ready ability to multiplex arrays of sensors, and the prospect for remote sensing. The variety of different designs and measurement schemes that may be employed using optical fibres provides the potential to create very sensitive and selective measurement techniques that can be deployed in real environments. The use of optical fibre sensors is finding increasing acceptance across a range of industrial sectors, with interest being driven by features of the technology that offer advantages over conventional measurement approaches in niche applications.

The presentation will discuss the development of fibre optic chemical sensors modified with the sensitive materials and introduce methods used for the deposition of the sensitive layers based on layer-by-layer adsorption and molecular imprinting techniques. Examples of the practical applications of the developed fibre-optic chemical sensors in bio-medical field will be provided.

10111-108, Session 27

Hypervelocity time-of-flight characterisation of a 14GS/s histogramming CMOS SPAD sensor *(Invited Paper)*

Neil Finlayson, Tarek Al Abbas, The Univ. of Edinburgh (United Kingdom); Francescopaolo Mattioli Della Rocca, University of Edinburgh (United Kingdom); Oscar Almer, The Univ. of Edinburgh (United Kingdom); Salvatore Gnecchi, SensL Technologies Ltd. (Ireland); Neale A. W. Dutton, STMicroelectronics (R&D) Ltd. (United Kingdom); Robert K. Henderson, The Univ. of Edinburgh (United Kingdom)

Time correlated single photon counting (TCSPC) involves recording of ultra-fast optical phenomena with very fine time resolution. Applications include time-of-flight (TOF) range measurement and fluorescence sensing. Performing TCSPC on a single silicon chip allows integration of arrays of single photon avalanche diode (SPAD) detectors, timing channels, and signal processing. High speed Time-to-Digital Converters (TDCs) are key elements. Elshazly et al have achieved stand-alone TDC throughput of 750 MS/s with a switched ring oscillator architecture [1]. Niclass et al reported

a TOF system-on-a-chip in which optical throughput of 100 MS/s was achieved [2].

Our TCSPC sensor features a 32x32 SPAD array, a 14 GS/s TDC and on-chip histogram generation [3]. Events are continuously recorded on-chip in 264 70 ps-wide histogram bins. With 80 SPADS enabled we measure optical mean/peak throughput of 23/39 photon events per 26 ns histogram cycle (0.87/1.48 GS/s).

High TDC throughput enables the device to be operated in Doppler mode with pulse-trains moving at hypervelocity speeds relative to the operational sensor frequency. Electrical signals of 50 kHz are resolved by the TDC module. Optical frequency signals of 1 kHz are resolved, corresponding to a TOF velocity resolution of 15.8 km/s.

Support for this work from EPSRC UltraImage project EP/M006859/1 and ST Microelectronics is gratefully acknowledged.

[1] A. Elshazly, S. Rao, B. Young, and P. K. Hanumolu, "A 13b 315fs rms 2mW 500MS/s 1MHz bandwidth highly digital time-to-digital converter using switched ring oscillators," Dig. Tech. Pap. - IEEE Int. Solid-State Circuits Conf., vol. 55, pp. 464–465, 2012.

[2] C. Niclass, M. Soga, H. Matsubara, M. Ogawa, and M. Kagami, "A 0.18-?m CMOS SoC for a 100-m-range 10-frame/s 200? 96-pixel time-of-flight depth sensor," IEEE J. Solid-State Circuits, vol. 49, no. 1, pp. 315–330, 2014.

[3] N. A. W. Dutton, S. Gnecchi, L. Parmesan, A. J. Holmes, B. Rae, L. A. Grant, and R. K. Henderson, "A time-correlated single-photon-counting sensor with 14GS/s histogramming time-to-digital converter," Dig. Tech. Pap. - IEEE Int. Solid-State Circuits Conf., vol. 58, pp. 204–205, 2015.

10111-109, Session 27

International optical clock comparison via coherent long-haul fiber links *(Invited Paper)*

Paul-Eric Pottie, Observatoire de Paris, Ctr. National de la Recherche Scientifique (France); Olivier Lopez, Lab. de Physique des Lasers, Univ. Paris 13 (France) and Ctr. National de la Recherche Scientifique (France); Jochen Kronjaeger, National Physical Lab. (United Kingdom); Gesine E. Grosche, Harald Schnatz, Physikalisch-Technische Bundesanstalt (Germany); Nicolas Quintin, Lab. de Physique des Lasers, Univ. Paris 13 (France) and Ctr. National de la Recherche Scientifique (France); Won-Kyu Lee, Korea Research Institute of Standards and Science (Korea, Republic of); Sebastian Koke, Alexander Kuhl, Physikalisch-Technische Bundesanstalt (Germany); Rosa Santagata, Observatoire de Paris, Ctr. National de la Recherche Scientifique (France); Anne Amy-Klein, Lab. de Physique des Lasers, Univ. Paris 13 (France) and Ctr. National de la Recherche Scientifique (France)

We have built first an international long-haul coherent fiber link between the german and the french National metrology institutes, via 1415 km of telecom fibers, including 710 km with parallel data traffic. We show that the relative frequency noise of the link is negligible compared to the one of the optical clocks after a few second of measurement only, and that the link induces no systematic relative frequency shift at the level of 2E-19.

We report here on the first international remote optical lattice clocks comparison that we achieved with this fiber link. We show that the comparison is limited by the clocks' uncertainty and stability themselves. We obtained a fractional uncertainty of two parts in 2E-17 after only 1000 s averaging time, which is already orders of magnitude faster than any other frequency transfer mean so far.

In addition a second international link between NPL and SYRTE has been built, via approximately 800 km of dedicated telecom fibers. We will show the latest results we obtained with these two long haul international optical links and show that multiple optical clock are made possible with these two combined links.

The capability of performing high resolution international clock comparisons paves the way for a redefinition of the unit of time and an all-optical dissemination of the second.

10111-110, Session 27

Microscale whispering gallery-mode lasers for sensing applications *(Invited Paper)*

Tindaro Ioppolo, Southern Methodist Univ. (United States)

Micro-scale whispering gallery mode lasers are demonstrated as sensors for remote sensing. We exploit its potential applications in the field of biological and mechanical engineering and different remote sensing applications will be reported. These micro-resonators are fabricated by mixing a solution of rhodamine 6G and methanol with different polymers. The micro-resonators are optically pumped using a Nd:YAG laser and their emission spectrum is observed using a spectrometer. The excited optical resonances are very sensitive to a change in the morphology of the resonators. Therefore, any perturbation of the morphology of the resonator such as size shape and index of refraction leads to a shift of the frequency of the optical resonances. By tracking the shift of the optical resonances, the external physical effect causing the morphology change can be monitored.

10111-111, Session 27

Long time ageing tests of DFB ridge laser diodes emitting at 852nm and 894nm for cesium atomic clocks *(Invited Paper)*

Patrick Resneau, Nicolas von Bandel, Michel Garcia, Yannick Robert, Eric Vinet, Michel Lecomte, Olivier Drisse, Olivier Parillaud, Michel Krakowski, III-V Lab. (France)

Time-frequency applications need high accuracy and high stability clocks. Compact industrial optically pumped Cesium beam standards are promising to address various demands. However, the stability of these clocks relies strongly on the performances of laser diodes that are used for optical pumping and detection. This issue has led the III-V Lab to commit to the European Euripides "LAMA" project that aims to provide competitive compact optical Cesium clocks. We have designed, fabricated and tested Ridge Distributed-Feedback (DFB) laser diodes at 894nm (D1 line of Cesium) and 852nm (D2 line), based on a Al-free active region comprising one GaInAsP quantum well grown by MOVPE. The use of D1 line for pumping will provide simplified clock architecture compared to D2 line pumping thanks to simpler atomic transitions and larger spectral separation between lines in the 894nm case. The laser modules should provide narrow linewidth (<1MHz), very good reliability and be insensitive to optical feedback. We have achieved both wavelengths with laser characteristics showing the required specifications.

In order to address the long term reliability of these lasers, long duration ageing tests (more than one year targeted) are being carried out for both wavelengths at 20mW and 25°C. The laser diodes have been ageing for 3120 hours (D1 line) and 4950 hours (D2 line) with very low increase of the operating current, almost linear with time, after a stabilization phase. Lasers designed for D1 and D2 Cesium lines show a maximum increase of respectively 0.1% (0.1mA) and 0.5% (0.5mA) per 1000hours.

10112-1, Session 1

Nanophotonic design for 2D and quantum materials *(Invited Paper)*

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

Design of the resonant optical response of ultrathin two-dimensional materials and heterostructures is enabling scientific exploration of new materials phenomena. As an example, demonstrate near-unity, broadband absorbing optoelectronic devices using sub-15 nm thick transition metal dichalcogenides (TMDCs) of molybdenum andtungsten as van der Waals semiconductor active layers. Specifically, we report that near-unity light absorption is possible in extremely thin (<15 nm) van der Waals semiconductor structures by coupling to strongly damped optical modes of semiconductor/metal heterostructures. We further fabricate Schottky junction devices using these highly absorbing heterostructures and characterize their optoelectronic performance. Our work addresses one of the key criteria to enable TMDCs as potential candidates to achieve high optoelectronic efficiency. We also report mid-infrared spectroscopy measurements of an electrostatically gated topological insulator, in which we observe several percent modulation of transmittance and reflectance of (Bi1-xSbx)2Te3 films as gating shifts the Fermi level. Infrared transmittance measurements of gated (Bi1-xSbx)2Te3 films were enabled by use of an epitaxial lift-off method for large-area transfer of TI films from the infrared-absorbing SrTiO3 growth substrates to thermal oxidized silicon substrates. We combine these optical experiments with transport measurements and angle-resolved photoemission spectroscopy to identify the observed spectral modulation as a gate-driven transfer of spectral weight between both bulk and topological surface channels and interband and intraband channels. We develop a model for the complex permittivity of gated (Bi1-xSbx)2Te3, and find a good match to our experimental data. These results open the path for layered topological insulator materials as a new candidate for tunable infrared optics and highlight the possibility of switching topological optoelectronic phenomena between bulk and spin-polarized surface regimes.

10112-2, Session 1

Simultaneously laser and anti-laser *(Invited Paper)*

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

No Abstract Available

10112-3, Session 1

Contribution to the world of photonics by atomic engineering of III-V semiconductor for quantum devices from deep-UV to THz (200 nm to 300 microns) *(Invited Paper)*

Manijeh Razeghi, Northwestern Univ. (United States)

No Abstract Available

10112-5, Session 2

Non-reciprocal wave propagation in zero-index materials *(Invited Paper)*

Andrea Alù, Dimitrios Sounas, Li Quan, The Univ. of Texas at Austin (United States)

Moving media have recently attracted attention for their ability to break reciprocity without magnetic materials. By spinning air in an acoustic cavity, it was recently shown that it is possible to realize an acoustic circulator [R. Fleury, D. Sounas, A. Alù, Science 343, 516 (2014)], with applications for sonars and medical imaging devices. Similarly, by effectively imparting angular momentum to microwave and optical resonators through spatiotemporal modulation, it is possible to induce strong non-reciprocity, with groundbreaking applications in the design of full-duplex communication systems [N. Estep, D. Sounas, J. Soric, A. Alù, Nature Physics 10, 923 (2014)]. Here we show that the non-relativistic Fresnel-Fizeau effect at the basis of these mechanisms can be boosted in epsilon-near-zero (ENZ) media, due to their small intrinsic refractive index. This is a different scenario than resonant structures, where the Fresnel-Fizeau effect is boosted by the effectively large wave-matter interaction distance, even for large intrinsic refractive index for the moving medium. Our results open a new venue to use zero-index metamaterials, and can become practically important in the realization of non-reciprocal imaging systems with built-in isolation and protection from reflections.

10112-6, Session 2

Patterning metamaterials for fast and efficient single-photon sources

Oksana A. Makarova, Mikhail Y. Shalaginov, Simeon Bogdanov, Urcan Guler, Alexandra Boltasseva, Alexander V. Kildishev, Vladimir M. Shalaev, Purdue Univ. (United States)

Solid state quantum emitters promise to make fast on-demand single-photon sources an attainable reality. The improvement in photon emission and collection efficiencies for quantum emitters, such as nitrogen-vacancy (NV) centers in diamond, can be achieved by using near-field coupling to nanophotonic structures. Plasmonic metamaterial structures with hyperbolic dispersion have been previously demonstrated to possess a large photonic density of states for a wide range of wavelengths. This significantly increases the NV center decay rates. However, the far-field collection also requires the outcoupling of electromagnetic waves propagating in the metamaterial. We propose a nano-groove based structure fabricated into a hyperbolic metamaterial to improve the outcoupling efficiency of the emissions from a nanodiamond with a single NV center. Optimization of the nanostructure's geometric parameters was performed using a finite element method. The resulting designs strongly increased the coupling of NV center fluorescence into free space modes. These designs can be utilized to achieve highly efficient and low-jitter single-photon sources based on a variety of emitters.

10112-7, Session 2

Study of gold and silver monomer and dimer nano-elliptic rings use in plasmonic waveguides in near-infrared spectrum

Tofiq Nurmohammadi, Karim Abbasian, Reza Yadipour, Univ. of Tabriz (Iran, Islamic Republic of); Behzad Sardari, Sabanci Univ. (Turkey)

The diffraction limit of the light is known as a major challenge in dimensional reduction of the conventional electronical and optical devices to nano-electronics and nano-optics scale, however it is possible to resolve the problem by utilizing surface plasmon polariton (SPP), which is propagating, dispersive electromagnetic wave coupled to the electron plasma in a conductor and dielectric interface. In other hand, the SPPs waves are propagating on the interface of metal and dielectric material due to interaction of the photons with free electrons in the metals, which can carry electromagnetic energy and should be confined in interface in a subwavelength limit. In this paper, we investigated plasmonic waveguide in near infra-red region especially at original (?=1310 nm) and also communication band (?=1530 nm) using gold or silver nano elliptic rings. With proper geometrical properties it is possible to shift localized surface plasmon resonance to desired wavelength. Three-dimensional simulations utilizing the finite-difference time-domain algorithm are used to determine the set of geometrical parameters of Ag and Au nano elliptic rings obtaining localized surface plasmon resonance at 1310 and 1550 nm. Employing different configuration of silver and gold nano square rings chain, waveguides are designed and -3dB transmission loss coefficients and group velocities of different modes are obtained. Furthermore, difference between monomer rings and dimer ring are expressed.

10112-8, Session 2

Shaping laser pulses with graphene-integrated metasurfaces *(Invited Paper)*

Gennady B. Shvets, Shourya Dutta Gupta, Cornell Univ. (United States); Nima Dabidian, The Univ. of Texas at Austin (United States)

Plasmonic metasurfaces enhance light-matter interaction by focusing light into extremely subwavelength dimensions. These carefully designed structures have been used in extremely thin optical component which can mold the wavefront, with exciting applications in optical lenses, beam steering, and biosensing applications. Adding dynamic tunability to these devices opens up the possibility for new application in single pixel detection and 3D imaging as well as optical modulators and switches. However the existing approaches for designing active optical devices in infrared, are either slow or have small refractive index change. Integrating plasmonic metasurfaces with single-layer graphene (SLG) opens exciting opportunities for developing active plasmonic devices because the amplitude and phase of the transmitted and reflected light can be rapidly modulated by injecting charge carriers into graphene using field-effect gating. I will describe our recent experimental results demonstrating strong phase modulation of mid-infrared light. The phase shifting due to electric gating of the SLG was measured using a Michelson interferometer, and further utilized to demonstrate an electrically controlled (i.e. no moving parts) interferometry capable of measuring distances with sub-micron accuracy. Because of the potentially nanosecond-scale measurement time, active metasurfaces represent a promising platform for ultra-fast standoff detection. Finally, we demonstrate that, by the judicious choice of a strongly anisotropic metasurface, the graphene-controlled phase shift of light can be rendered polarization-dependent, thereby modulating the polarization state (e.g., the ellipticity) of the reflected light. These results pave the way for novel high-speed graphene-based optical devices and sensors such as polarimeters, ellipsometers, and frequency modulators.

10112-4, Session 3

Real and imaginary properties of epsilon-near-zero materials *(Invited Paper)*

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

No Abstract Available

10112-9, Session 3

Merging micro- and nano-optics *(Invited Paper)*

Harald Giessen, Univ. Stuttgart (Germany)

No Abstract Available

10112-10, Session 3

Intensity-dependent modulation of optically active signals in a chiral metamaterial

Sean P. Rodrigues, Shoufeng Lan, Lei Kang, Yonghao Cui, Patrick Panuski, Georgia Institute of Technology (United States); Shengxiang Wang, Wuhan Textile Univ. (China); Augustine M. Urbas, Air Force Research Lab. (United States); Wenshan Cai, Georgia Institute of Technology (United States)

A chiral metamaterial exhibits two absorptive resonances in the linear regime that can be spectrally modified when exposed to incremental intensities. The chiral metamaterial and its enantiomer experimentally demonstrate strong optically active responses in the linear regime, a maximum circular dichroism of 0.58 and an optical rotation of 25°. The two chiral enantiomers show near perfect mirror responses and strong correlations between experimental and simulated results. Modification of these linear chiroptical responses is achieved when input powers are increased. The spectral location of the resonances in the transmission spectra are shifted by up to 10 nm from a change in input power of 14.5 mW. This spectral shift leads to a change in transmission of 0.12 over the same change in power. Strong nonlinear optical rotation is observed at key spectral locations. A change of 14° in rotation is experienced when only a difference in 14 mW is applied through a metamaterial thickness of less than lambda/7. By manipulation of input powers incident on chiral metamaterials, active inflection of chiral signals can be achieved. The modulation of chiral signals offers potential for active optics such as optical switching and communications.

10112-11, Session 3

Spatial nonlinearity at low power in anisotropic metamaterial plasmonic slot waveguides

Gilles Renversez, Institut Fresnel (France) and Aix-Marseille Univ. (France); Mahmoud M. R. Elsawy, Institut Fresnel (France)

Nonlinear plasmonic slot waveguides (NPSWs) have drawn attention in the last decade due to the strong light confinement in the nonlinear dielectric core ensured by the surrounding metal regions, and to their peculiar nonlinear effects. Nevertheless, the experimental observation of plasmon-soliton waves in these NPSWs is still lacking. In our work, we propose and

study the improvement of symmetric NPSWs by the use of an anisotropic metamaterial core with a positive Kerr-type nonlinearity.

First, we demonstrate that for isotropic nonlinear cores with epsilon-near-zero (ENZ) permittivity the bifurcation threshold of the asymmetric mode is not reduced, as it is usually expected from ENZ properties, but increased from GW/m threshold to 100 GW/m one.

Second, when highly anisotropic diagonal ellipticals but realistic, core with a transverse ENZ component is considered, the bifurcation threshold is now reduced around the 10 MW/m limit gaining more than two orders of magnitude. This properties indicates a strong enhancement of the effective nonlinearity. Furthermore, the slope of the dispersion curve of the asymmetric mode stays positive suggesting a stable mode as confirmed by full vector nonlinear FDTD simulations allowing its use in possible applications at realistic powers.

Third, we show that for hyperbolic nonlinear core, there is no physically meaningful asymmetric mode, and that the sign of the effective nonlinearity can become negative.

To get these results, we developed specific methods in order to compute the nonlinear stationary solutions that propagate in these anisotropic NPSWs. For the semi-analytical model we developed, we also provide a closed analytical formula for the effective nonlinearity.

10112-12, Session 3

Spatial mode filter with hyperbolic-cladded waveguide

Ying Tang, Zheng Xi, Optics Research Group, Technische Univ. Delft (Netherlands); Man Xu, Optics Research Group, Technische Univ. Delft (Netherlands) and TNO (Netherlands); Aurèle J. L. Adam, H. Paul Urbach, Optics Research Group, Technische Univ. Delft (Netherlands)

Hyperbolic Meta-Materials (HMMs) are anisotropic materials with permittivity tensor that has both positive and negative eigenvalues. Their exotic hyperbolic dispersion property is the key to numerous emerging nano-photonics applications. In this work, we propose an unusual spatial mode filter by using HMM as cladding material. The propagation constant of lower order modes are large enough to propagate in the HMM cladding material, such that they are turned into leaky modes. At the same time, higher order modes with smaller propagation constants remain confined in the core and, therefore, are guided.

The dispersion relation of guided mode in hyperbolic cladding waveguide is solved. The result shows that in the type II hyperbolic dispersion frequency region, no lower order modes are guided in the core. The mode filtering property is further studied as a function of the filling factor. The result shows that the order of the lowest order guided mode increases for smaller filling factor. Also with smaller filing factor, the propagation length of the same order can be an order of magnitude higher.

We confirm this particular mode filtering using finite element method simulation. Both effective HMM and real multilayer HMM cladded waveguide at 1550 nm are simulated and the results show good agreement with our predictions.

To summarize, we propose a novel mode filter waveguide by using HMM as cladding material. This design may be used to excite and separate spatial modes in Spatial-Division Multiplexing (SDM) technique.

10112-13, Session 4

High-quality-factor photonic crystal cavities in a hybrid silicon-on-lithium-niobate platform

Jeremy D. Witmer, Jeff T. Hill, Amir H. Safavi-Naeini, Stanford Univ. (United States)

Lithium niobate (LN) is a well-understood and heavily used optical material with a variety of useful properties such as its linear electro-optic effect, chi(2) nonlinearity, and piezoelectric effect. However, LN is a difficult material to etch and patterning high quality optical devices is challenging. Here we present results on the design and fabrication of a photonic crystal cavity made in a hybrid silicon-on-lithium-niobate material system. This material system takes advantage of the useful properties of LN, while simultaneously leveraging expertise in silicon etching and removing the need to pattern LN. These devices use the index contrast between silicon and LN to guide and confine optical resonances in a thin film of silicon bonded on top of LN. The photonic crystals have optical wavelength scale mode volumes and simulated quality factors greater than 10^6, with measured quality factors above 10^5. Due to the electro-optic effect in LN, these devices exhibit coupling between the optical resonance frequency and the electric field of adjacent electrodes. We show that such a system can yield a simulated electro-optic coupling rate of 0.6 GHz/V (4 pm/V). We expect resonators of this type to have a wide range of applications, including achieving large coupling to isolated rare-earth ions (such as Er^{3+}) at telecom frequencies, efficient three-wave mixing in resonant silicon devices, and sensitive acousto- and electro-optic modulation.

10112-14, Session 4

Demonstrating negative refraction in a three-dimensional core-shell photonic crystal lattice

Victoria Chernow, Ryan Ng, Julia R. Greer, California Institute of Technology (United States)

Vast interest in negative refraction has been motivated by the possibility of creating a "superlens" as proposed by Pendry (Phys. Rev. Lett. 85, 3966 (2000)) – his theoretical work showing that a material capable of negative refraction amplifies evanescent waves, allowing this material to act as a lens with a resolution not limited by working wavelength. While theory and experiment have shown that certain metamaterials and photonic crystals (PhCs) can act as superlenses, actually achieving negative refraction in the optical and infrared range remains a challenge; most metamaterials employ lossy metal elements limiting their application, and most PhC structures found to exhibit negative refraction, though made of positive index dielectric materials, are 2D. The subwavelength imaging of a 3D object requires a 3D PhC capable of negative refraction, and based on the numerical simulations of Luo, Johnson, and Joannopoulos (Appl. Phys. Lett. 81, 2352 (2002)), we demonstrate the fabrication and characterization of a polymer-Germanium core-shell 3D photonic crystal lattice which exhibits nearly all angle negative refraction over a large frequency range in the mid-infrared. The 3D photonic crystal resembles a BCC lattice of air cubes in dielectric media and was fabricated using two-photon lithography direct laser writing followed by sputtering. The band gap properties of the lattice were verified through FTIR spectroscopy reflectance measurements, and negative refraction was demonstrated through the use of angle resolved mid-IR transmission measurements.

10112-15, Session 4

Kerr nonlinear layered photonic crystal coatings

Arthur R. McGurn, Western Michigan Univ. (United States)

Theoretical studies are presented of the properties of the electromagnetic fields of layered one dimensional photonic crystal coatings on interfaces and on mirrors. The systems treated consist of a photonic crystal layering of Kerr nonlinear dielectric medium alternating with linear dielectric medium. In the absence of mirrors and interfaces the photonic crystal coating exhibits a series of pass and stop bands in the transmission of electromagnetic waves through the one dimensional photonic crystal. When the photonic crystal layering is added as a coating, regions of high and low field intensity are found within the coating. The regions of high field intensity within the coating are associated with pass bands of the photonic crystal, and the regions of low field intensity within the coating are associated with stop bands of the photonic crystal. In addition, certain excitations arising solely from the Kerr nonlinearity are found within the stop band regions of the one-dimensional photonic crystal. The origins and nature of these excitations are discussed and the enhanced fields associated with them within the coatings are studied with regards to the system Kerr nonlinearity. A mapping is presented of the nature of the excitations generated within the layering in the parameter space of the linear and nonlinear components of the Kerr media dielectric function. The enhancements due to stop band excitations are studied as a function of the number of layers within the coating and the optimum conditions for field enhancement within a coating are determined. The nature of the wave function of the modes excited within the stop bands of the coating is studied as a function of the stop bands in which they occur. Discussions are made of the significance of these results to field enhancement due to nonlinearity, surface enhanced Raman spectroscopy, and in the generation of second harmonics at mirror surfaces and at interfaces.

10112-17, Session 4

Development of near-infrared narrow-band thermal emitters on MgO-substrates based on silicon rod-type photonic crystals

Masahiro Suemitsu, Osaka Gas Co., Ltd. (Japan); Takashi Asano, Tatsunori Tsutsumi, Menaka De Zoysa, Susumu Noda, Kyoto Univ. Graduate School of Engineering (Japan)

In order to realize highly efficient thermophotovoltaic generation systems, it is necessary to develop selective thermal emitters whose emission is concentrated in a range just above the bandgap of the photovoltaic cells. For this purpose, we have demonstrated narrow-band thermal emitters by using rod-type silicon photonic crystals (PC) supported by 1 um-thick SiO2 membranes. Although the emitters show emission concentrated in near-infrared range at 1300 K, their sizes are limited to be smaller than 1 mm square because of the vulnerability of the membranes. In this abstract, in order to enable fabrication of large area emitters, we investigate silicon rod-type PCs supported by MgO-substrates. MgO has a high melting point of 3124 K and have a low emissivity from visible to mid-infrared. We deposited 500 nm-thick polycrystalline-silicon on 300 um-thick MgO-substrates by LP-CVD method, and formed the PC patterns by an electron beam lithography and a dry etching technique. The fabricated emitters showed low emissivity below 0.05 between 1.4 and 5.9 um while peak emissivity at 0.8 um was beyond 0.9 at 1300 K. The emission in the wavelength range > 5.9 um can be made less than 18% of the total emission by optimizing the substrate thickness while maintaining enough stiffness for large area structures. These results indicate that the structure, Si-rods on MgO-substrates, enables to enlarge the emitter up to several inches while maintaining enough thermal emission characteristics for thermophotovoltaic systems.

10112-18, Session 4

High-quality-factor thermal emitters

Mathilde Makhsiyan, ONERA (France) and Ctr. de Nanosciences et de Nanotechnologies (France); Patrick Bouchon, Julien Jaeck, Riad Haïdar, ONERA (France)

Metasurfaces have been studied for their ability to artificially tailor an electromagnetic response on various spectral ranges and to achieve unprecedented light properties. In particular, the idea to control thermal emission has been a major topic of interest, since usual thermal sources following Planck's law exhibit a wideband and omnidirectional emission. For instance, Metal-Insulator-Metal metasurfaces that spatially and spectrally control the emissivity up to the diffraction limit have been demonstrated [1]. However, for many practical applications, such as biochemical sensing, thermal emitters with very high quality factor (Q) emission are needed to efficiently emit in the targeted spectral range, without any wasted emission outside the band. Here, we experimentally demonstrate a high-Q mid-infrared thermal emitter that exhibits a very narrow emissivity at the resonance wavelength (Q > 80) and a high rejection ratio outside the emission band. The resonance can be tuned by changing the geometry of the structure in order to obtain multispectral emitters. Our structures are numerically computed, fabricated in clean room and experimentally characterized by a dedicated emission measurement setup that provides both spectral and spatial information.

[1] Makhsiyan, M., Bouchon, P., Jaeck, J., Pelouard, J. L., & Haïdar, R. (2015). Shaping the spatial and spectral emissivity at the diffraction limit. Applied Physics Letters, 107(25), 251103.

10112-19, Session 5

Nanophotonics with new materials and metasurface designs *(Invited Paper)*

Urcan Guler, Harsha Reddy, Krishnakali Chaudhury, Amr M. Shaltout, Alberto Naldoni, Mikhail Y. Shalaginov, Simeon Bogdanov, Alexander V. Kildishev, Alexandra Boltasseva, Vladimir M. Shalaev, Purdue Univ. (United States)

Recent activities in the field of plasmonics are focused on the materials research to identify and optimize materials for application-specific requirements. These efforts have made a significant contribution towards realization of plasmonic components that can be utilized in real world applications. In this talk, we will present transition metal nitrides as refractory plasmonic materials for applications in harsh environments. Optimization and characterization of samples produced via physical vapor deposition and nitridation of oxides will be discussed. Besides, single crystalline, epitaxially grown silver thin films on optically transparent substrates will be introduced. Temperature dependence of the optical properties of plasmonic thin films up to melting points will be presented. The performance of plasmonic components at elevated temperatures will be outlined. In addition, light control through wave-front engineering via new metasurface designs will be discussed.

10112-20, Session 5

Flat and conformal optics using dielectric metasurfaces *(Invited Paper)*

Andrei Faraon, California Institute of Technology (United States)

Flat optical devices based on lithographically patterned sub-wavelength dielectric nano-structures provide precise control over optical wavefronts, and thus promise to revolutionize the field of free-space optics. I discuss our work on high contrast transmitarrays and reflectarrays composed of silicon nano-posts located on top of low index substrates like silica glass

or transparent polymers. Complete control of both phase and polarization is achieved at the level of single nano-post, which enables control of the optical wavefront with sub-wavelength spatial resolution. Using this nano-post platform, we demonstrate lenses, waveplates, polarizers, arbitrary beam splitters and holograms. Devices that provide multiple functionalities, like simultaneous polarization beam splitting and focusing are implemented. By embedding the metasurfaces in flexible substrates, conformal optical devices that decouple the geometrical shape and optical function are shown. Multiple flat optical elements are integrated in optical systems such as planar retro-reflectors and Fourier lens systems with applications in ultra-compact imaging systems. Applications in microscopy and the prospects for tunable devices are discussed.

10112-21, Session 5

Planar dielectric metasurfaces for immersion optics *(Invited Paper)*

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Using immersion lenses is a common approach to enhance the resolving power in various fields of optics such as microscopy and lithography. However, conventional immersion lenses are bulky, high-cost and are typically designed for only a few specific immersion liquids. The development of meta-surfaces provides a promising approach to manipulate light in a compact configuration, enabling many optical devices such as polarizers, waveplates and lenses. These are mainly focused in the near-infrared or the long-wavelength region of the visible spectrum due to fabrication challenges and intrinsic losses of materials used. Here, we demonstrate oil immersion planar lenses with a numerical aperture of 1.1 at visible wavelengths. The lenses provide diffraction-limited focal spots with Strehl ratios higher than 0.9 and 0.8 at their design wavelengths of 532 nm and 405 nm, respectively. Fabrication is based on an atomic-layer deposition (ALD) of TiO_2. The loss of TiO_2 in the visible is negligible and the surface roughness is well-controlled due to the precise monolayer growth of the TiO_2 film. By applying the lens (designed at 532 nm) in a confocal scanning microscopy setup, we are able to achieve high-quality images with sub-wavelength resolution. It should be noted that this lens can be efficiently tailored for any liquid. We demonstrate another design for water-immersion lenses, which are highly applicable to super-resolution bio-imaging applications. The compactness and design flexibility of this platform is highly promising for widespread applications in imaging and spectroscopy.

10112-22, Session 6

Imaging using the memory effect in multi-core fibers *(Invited Paper)*

Demetri Psaltis, Nicolino Stasio, Donald B. Conkey, Christophe Moser, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We will describe how the memory effect in multicore fibers can be used for novel imaging modalities

10112-23, Session 6

Design of a nanopatterned long focal-length planar focusing collector for concentrated solar power

Qing Ding, Univ. of Illinois at Urbana-Champaign (United States); Aakash Choubal, Univ of Illinois at Urbana-Champaign (United States); Kimani C. Toussaint Jr., Univ. of Illinois at Urbana-Champaign (United States)

Concentrated solar power (CSP) facilities heavily utilize parabolic troughs to collect and concentrate sunlight onto receivers that deliver solar thermal energy to heat engines for generating electricity. However, parabolic troughs are bulky and heavy and result in a large capital investment for CSP plants, thereby making it difficult for CSP technology to be competitive with photovoltaics. We present the design of a planar focusing collector (PFC) with focal length beyond the micron scale. The PFC design is based on the use of a nanostructured silver surface for linearly polarized single-wavelength light. The designed PFC consists of 1D metallic nanogrooves on a dielectric substrate. The geometric properties, namely the width and depth, of a single-unit nanogroove allows for full control of the optical phase at desired spatial coordinates along the nanogroove short-axis for a single wavelength. Moreover, we show numerically that such phase control can be used to construct a phase front that mimics that of a cylindrical lens with only minor loss, which is the desired focusing behavior for a parabolic trough alternative. In addition, we determine the conversion efficiency at long focal lengths by evaluating the ratio of the collected radiant flux to the incoming radiant flux. Finally, we also examine the focusing behavior across multiple wavelengths and suggest a design approach to minimize chromatic focusing errors. Our work shows how nano-optics and plasmonics could contribute to this important area of CSP technology.

10112-24, Session 6

Mid-infrared high-efficiency plasmonic flat lens

Alireza Safaei, Michael N. Leuenberger, Debashis Chanda, Univ. of Central Florida (United States)

Conventional optical elements such as lenses, waveplates and polarizers function by adding phase delays to the propagating light. The thicknesses of these dielectric optical components are much larger than wavelength to accumulate 0-ϖ phase shift. Moreover, spherical aberration and diffraction limit restrict their usage in integrated photonics circuits. Metasurface based lenses change the phase of transmitted and reflected electromagnetic waves significantly at resonance by exciting surface plasmons on the metallic arrays with thickness much lower than the wavelength of the incident light. However, previous demonstrations of plasmonic lens suffer from low transmission efficiency (< 20%) due to the high plasmonic losses. We overcame this shortcoming to some extend by engineering plasmonic coupling and demonstrated a relatively high 75% transmission in the mid infrared spectral domain. In this proposed work, coupled one dimensional array of gold disks with variable diameters have been employed to add varying phases to the transmitted light in order to create the phase front curvature in mid-IR wavelength range needed for the focusing of the incident radiation. The designed nanostructured surface achieves a resolution beyond the diffraction limit in thin-film planar geometry. The focal point, resolution and transmission efficiency can be tuned by various parameters such as period, diameters, and the size of the disks. The confocal measurement method has been performed to measure the far field focal volume of the fabricated lens, which is in good agreement with the theoretical results. Thin-film planar layout and subwavelength resolution mitigate the limitations of conventional optical elements.

10112-25, Session 6

Structural color tuning in a Ag/TiO2 nanoparticle one-dimensional photonic crystal induced by electric field

Eduardo Aluicio-Sarduy, Istituto Italiano di Tecnologia (Italy); Simone Callegari, Politecnico di Milano (Italy); Diana Gisell Figueroa del Valle, Andrea Desii, Ilka Kriegel, Istituto Italiano di Tecnologia (Italy); Francesco Scotognella, Politecnico di Milano (Italy)

The active tuning of the light transmission properties of photonic structures is very attractive for the realization of electro-optic switches and devices for colour manipulation. Moreover, the employment of a stimulus and the electric field for the photonic structure color tuning is promising because of its versatility and simple applicability. In this work we present the tuning in a photonic crystal device made by alternating layers of Silver and Titanium dioxide nanoparticles. The device shows shifts of around 10 nm for an applied voltage of 10 V only. Due to the electric field the accumulation of charges at the metal/dielectric interface leads to an effective increase of the charges contributing to the plasma frequency in Silver. This increase initiates a blue shift of the Silver plasmon band with a concomitant blue shift of the photonic band gap as a result of the change in the Silver dielectric function, that means a decrease of the effective refractive index. The fabricated devices are characterized by atomic force microscopy, scanning electron microscopy, and ultrafast pump-probe spectroscopy. These results are a demonstration of a new type of active colour tuning in Silver/Titanium dioxide nanoparticle based photonic crystals and open the route to metal/dielectric based photonic crystals as electro-optic switches.

10112-26, Session 7

Photonic crystals for sensing and imaging *(Invited Paper)*

Thomas F. Krauss, Univ. of York (United Kingdom)

Nanophotonic concepts have have tremendous potential for improving the already high performance of photonic biosensors in terms of versatility and functionality. Here, we introduce a novel silicon photonic sensing geometry based on a chirped guided mode resonance which affords a simple readout without spectrometer. Secondly, we demonstrate the combination of electrochemical and photonic sensing in an entirely new sensing modality.

10112-27, Session 7

Optical coupling effects on the performance of 3D SERS bio-sensors

Aleksandr Polyakov, Anita Rogacs, Hewlett-Packard Labs. (United States)

While a wide range of substrate formats have been proposed for surface enhanced Raman scattering (SERS) applications, the challenge remains in designing a reproducible high efficiency SERS substrate. In part, this is due to the disconnect between the local field enhancement spectra and the localized surface plasmon resonance (LSPR) spectra commonly used in biosensors. While dark modes have been identified as possible explanation for this disconnect, it remains unclear how much they contribute to the optical coupling and to the overall sensor performance.

In this work, we report a systematic study of optical coupling in SERS substrates by measuring the sensor performance across the visible and near-infrared spectral range together with the LSPR response. The sensors used were fabricated by nanoimprint lithography to produce a flexible polymer pillar structures coated with gold. Upon exposure and evaporation of a liquid containing an analyte, the pillars close at the top (in a tweezer-like fashion) generating high SERS signal from the molecules within gaps between the neighboring pillar tips. The resulting field enhancement was measured across the VIS-NIR excitation from a set of compounds with peaks covering a wide spectral range. Further adjusting the nanostructure parameters and the illumination conditions to match the measured optimum coupling regime in agreement with the finite difference time domain (FDTD) model, we have improved the sensor performance to detect melamine, cyromazine, ammeline, 3-amino-1,2-,4-triazine, and amitrol spiked into 2% milk at concentrations ranging from 0.01 to 1 mM in a portable Raman system.

10112-28, Session 7

Enhanced photoluminiscence and surface-enhanced Raman effect in SnS/Sn nanohybrids

R. Gandhimathi, Anita R. Warrier, AMET Univ. (India)

Semiconductor/metal nanohybrids exhibit several interesting properties with tunable absorption, photoluminiscence and enhanced RAMAN mode intensity. In the present investigation, semiconductor/metal nanohybrid structures were synthesized by wet chemical methods. Tin sulfide (SnS) nanospheres (~ 50 nm to 100 nm) with different particle size were prepared by changing the pH of the solution. Tin (Sn) nanoparticle

(~15 nm) were synthesized by a simple chemical route using sodium borohydride (NaBH4) as the reducing agent. The morphology of Sn nanostructures varied from nanoparticles to nanosheets with increase in NaBH4, accordingly the surface plasmon resonanance peak shows the transverse and longitudinal mode respectively. SnS nanoparticles were attached with Sn nanostructures by growing the Sn nanoparticles in SnS dispersed in polyvinyl pyrolidene solution at room temperature. The growth of SnS/Sn nanohybrids is well depicted in the HRTEM image. The coupling of the plasmonic structure with semiconductor nanoparticles leads to enhanced optical absorption and photoluminescence (with peak at ~ 550 nm) in the nanohybrids. The strong interaction between the excitons and plasmons in the nanohybrids also leads to Raman enhancement in the SnS nanoparticles. Such structures have wide spread application as biomedical imagers and sensors.

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10112-29, Session 7

Silicon-plasmonic-integrated mid-infrared sensor using CMOS technology

Mohamed A. Swillam, Mohamed M. Sherif, The American Univ. in Cairo (Egypt)

In this paper, we propose a compact design high sensitivity plasmonic sensor functional at the mid infrared spectral range. Instead of using conventional metals for generating plasmonic excitations, the plasmonic effects are experienced through using a doped Si platform. The structure of the sensor is composed of a doped silicon-insulator-doped silicon (SIS) waveguide configuration. There are several advantages of using a doped semiconductor instead of a conventional metal for plasmonic excitations in our sensor device. Metals are not CMOS compatible, while doped semiconductors are fully compatible with the CMOS fabrication technology, which suggests the possibility of integration of our sensor with the CMOS electronic components on the same chip. In addition, the plasma frequency in doped semiconductors is dependent on the free carrier concentration, whereas a given metal has a fixed plasma frequency value. So, the plasma frequency in doped Si is dependent on the doping levels. Our doped Si model uses a doping concentration of 5x1020 cm-3. Such a very high

doping tunes the plasma frequency to a wavelength of 3 microns, thus, the material is characterized by its high reflectivity in the mid infrared range. We use this property in order to generate a resonance effect in the mid infrared by coupling the light from the metal-insulator-metal waveguide to the rectangular slot which acts as our cavity. The sensing mechanism of our sensor is experienced through a shift of the resonance wavelength in response to the change in the refractive index of the surrounding medium. Our sensor can be used for the on-site detection of different gases in the mid infrared range with a very high sensitivity of 5000nm/RIU.

10112-30, Session 7

Improved light injection and enhanced Raman scattering in microfabricated opaque structures

Jonathan V. Thompson, Brett H. Hokr, Vladislav V. Yakovlev, Texas A&M Univ. (United States)

Spontaneous Raman scattering is a powerful tool for the remote detection and identification of various chemical materials. However, its usefulness in biological and other samples is severely limited because often the chemical of interest is contained deep within a highly scattering material. This highly scattering material rejects the pump light before adequate optical radiation can reach the chemical and produce Raman scattered light. By optically drilling a microscopic hole in the surface of the scattering material and focusing our pump laser into the hole, we show that the penetration depth and interaction time of the laser with the scattering sample is drastically increased. Because of this enhanced penetration depth and interaction time, a larger percentage of the incident pump light is converted to Raman scattered light, thereby producing a signal that is much easier to detect. In particular, we demonstrate enhancements of nearly two orders of magnitude more Raman scattered light by focusing our pump laser into a microscopic hole drilled in the surface of a barium sulfate sample. This approach gives us a method to more efficiently detect chemicals buried deep within a highly scattering medium.

10112-31, Session 7

Photo-induced heat-generation mechanism in Ag nanoparticles embedded in SiO2 and B-In2S3 matrix

Anita R. Warrier, AMET Univ. (India); Cherianath Vijayan, Indian Institute of Technology Madras (India)

Photoinduced heat generation mechanism in Ag nanoparticles

embedded in SiO2 and ?-In2S3 matrix

The photoinduced heat generation has applications in photothermal cancer therapy, optical storage, thermo-photovoltaics etc. Plasmonic nanostructures have high photothermal conversion efficiency compared to semiconductors and dielectric nanostructures. Using photothermal beam deflection technique we investigate the heat generation and transfer mechanism in Ag nanoparticles (plasmonic nanostructures with SPR peak at 435 nm) illuminated with beam whose wavelength matches with surface plasmon resonance. The heat generation and transfer mechanism in a plasmon is highly dependent on the surrounding medium. In this work we probe the photothermal conversion properties of individual metal (Ag) nanoparticle, semiconductor (?-In2S3) microflowers, dielectric (SiO2) nanostructures and Ag nanoparticles embedded in ?-In2S3 and SiO2 matrix. The heat generated from the Ag nanoparticles is much higher when embedded inside polymer encapsulated SiO2 and ?-In2S3 matrix than the individual nanoparticle assembly. The heat generation mechanism is shown to be an ultrafast process (picoseconds) when the Ag nanoparticles are embedded in a SiO2 matrix, while for individual Ag nanoparticles and Ag: ?-In2S3 complex the process is shown time delayed. The change is attributed to the resonant heat transfer mechanism. The measurements were carried out by illuminating the samples with pump beam of 445 nm. The refractive index gradient produced in the surrounding air due to thermal waves emanating from the sample is measured using a probe beam of wavelength 546 nm and a position sensitive quadrant cell detector.

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10112-32, Session 7

Imaging the magnetic near-field of light with an aperture probe

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The development of innovative photonic devices and metamaterials with tailor-made functionalities depends critically on our capability to characterize them and understand the underlying light-matter interactions. Thus, imaging all components of the electromagnetic light field with nanoscale resolution is of paramount importance in this area. Nowadays, the electric and the vertical magnetic field components of light can be measured with sub-wavelength resolution. This is achieved by scanning the sample surface with specific probes in a method known as scanning near-field optical microscopy (SNOM). However, within this toolbox, an unambiguous way of visualizing the horizontal magnetic field component has been missing.

We have answered this challenge by demonstrating experimentally that a hollow-pyramid circular aperture probe SNOM can directly image the horizontal magnetic field of light in simple plasmonic antennas – rod, disk and ring. These results are also confirmed by numerical simulations, showing that the probe can be approximated, in the first order, by a magnetic point-dipole source. This approximation substantially reduces the simulation time and complexity and facilitates the otherwise controversial interpretation of near-field images. Further, we use the validated technique to study complex plasmonic antennas and to explore new opportunities for their engineering and characterization. The applicability of this methodology is currently being extended beyond plasmonics structures.

Thus, the presented hollow-pyramid circular aperture based SNOM approach complements the existing techniques for imaging the different electromagnetic field components, by providing an opportunity to explore the tangential magnetic field of light with sub-wavelength resolution.

10112-33, Session 8

Diamond nanophotonics and high-power optics *(Invited Paper)*

Marko Loncar, Harvard School of Engineering and Applied Sciences (United States)

No Abstract Available

10112-34, Session 8

Photonic structures for interfacing color centers in diamond *(Invited Paper)*

Thomas Jung, Philipp Fuchs, Laura Kreiner, Jonas N. Becker, Johannes Görlitz, Christoph Becher, Univ. des Saarlandes (Germany)

Color centers in diamond, i.e. atomic-scale, optically active defects in the diamond lattice, have received large recent attention as versatile tools for solid-state-based quantum technologies. The most prominent example is the nitrogen vacancy (NV) center providing very long spin coherence times. On the other hand, silicon vacancy (SiV) centers have attracted large interest due to their spin-accessible optical transitions [1], the quality of their optical spectrum, i.e. narrow zero phonon lines and weak phonon sidebands [2], and their potential for all-optical coherent control, both in steady-state [3] and with ultrafast optical pulses [4].

A limitation of current experiments in bulk diamond, however, is the typically small photon collection efficiency of a few percent only. More efficient interfacing can be achieved in general by controlling the local density of states (LDOS) for color centers embedded in the diamond material. We will discuss two routes for LDOS control: 1. planar antenna structures, consisting of layers of dielectric and metal films, which modify the dipole emission characteristics and provide moderate spontaneous emission enhancement (Purcell) factors to yield large collection efficiencies; 2. photonic crystal cavities directly fabricated in the diamond material [5] which provide larger Purcell factors and also can be combined with metal surfaces to yield large output coupling efficiencies.

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10112-35, Session 8

Bloch surface-waves-induced fano resonance in magneto-optical response of magnetophotonic crystals

Irina V. Soboleva, Maria N. Romodina, Alexander I. Musorin, Andrey A. Fedyanin, M.V. Lomonosov Moscow SU (Russian Federation)

Magneto-optical effects such as Faraday and Kerr effects are known to significantly increase near the narrow spectral resonances. Among others, the one-dimensional magnetophotonic crystals (MPCs) can be considered as an example of the nanostructures providing this kind of enhancement at the photonic band gap edge, defect modes of the MPCs and in the vicinity of optical Tamm state resonance. MPCs also support Bloch surface waves (BSW) propagation. The proper polarization state of the incoming light is crucial for the BSW generation; the correct choice of the MPC parameters gives the way to observe the s-polarized BSW and p-polarized waveguide mode (WGM) of magnetophotonic crystal in the same spectral region. In this study, it is shown numerically and experimentally that if such resonances are spectrally close they can influence each other undergoing an external magnetic field. The Faraday rotation spectra, both measured and calculated, demonstrate the Fano-shape resonance corresponding to the BSW spectral position. The shape of the resonance depends on both the BSW excitation and the BSW and the WGM relative position and changes from a symmetric shape to asymmetric one while the incident angle increases. This indicates that the spectral dependence of the Faraday rotation angle depends not only on the BSW resonance in the structure, but also on coupling of the BSW with the WGM mode that is not excited in s-polarization of the incident light. The view of the resonance gives a way to determine the mutual spectral position of the BSW and WGM resonances.

10112-36, Session 8

All-silicon ultra-broadband infrared light absorbers

Kazim Gorgulu, Abdullah Gok, Mehmet Yilmaz, Kagan Topalli, Necmi Biyikli, Ali K. Okyay, Bilkent Univ. (Turkey)

Highly doped semiconductors are very promising materials of plasmonics with advantages over conventional metals in tunability and fabrication facility. Among these semiconductors, silicon has attracted great interest due to the benefits of integrated photonic devices including subwavelength interconnects, modulators, and emission sources. Using silicon as a material for MID-IR applications has also received great attention because it allows chip scale integration. There has been significant interest in broadband absorber structures for various applications. For electromagnetic wave absorbers, it is very important to have wide range of operation wavelength, and much of the work focuses on overcoming the narrowband limit through multiresonance or tapered metamaterial structures. However, the number of resonators combined within the same unit cell is limited and highly efficient and ultra-wideband absorbers have not previously been proposed or implemented in MID-IR region. In this study, we demonstrate ultra-broadband mid-infrared (MID-IR) absorbers based on low-resistivity silicon and show that broadband absorption originates from superposition of plasmonic and photonic modes supported by the structure. The absorbers, consisting of periodically arranged silicon gratings, are fabricated by using standard optical lithography and inductively coupled plasma (ICP) technique, allowing for large-area and cost-effective fabrication of micro-scale structures. Absorption wavebands in excess of 15 micrometers (5-20 μm) are demonstrated with more than 90% average absorptivity. The structures also exhibit broadband absorption performance even at high angles of incidence (? = 50°), and independent of polarization. Demonstrated structures are potential for infrared imagers, and sensing and light harvesting applications.

10112-37, Session 8

Broadband light absorber based on porous alumina structure covered with ultrathin iridium film

Bo Fang, Chenying Yang, Weidong Shen, Yueguang Zhang, Xu Liu, Zhejiang Univ. (China)

Here we propose a novel broadband absorber with high efficiency by depositing nanometer iridium (Ir) film onto porous anodic alumina (PAA) template so as to increase the optical path length of the incident light for its great absorption property. Distinguished from the narrow band absorber using sub-wavelength resonant dielectric nanostructures and excitation of the propagating surface plasmon (PSP), PAA with nanometer Ir film can present broadband absorption with high efficiency as a result of the superposition of many different plasmon-enhanced absorption peaks by utilizing light funneling. The average absorption is able to achieve as high as 93.4% for 400-1100nm wavelength band and 96.8% for improved structure of quadrangular frustum pyramid array. And not only the hexagonal latticed structures of PAA template but also many similar structures based on grating or holes with square latticed or other latticed mode are able to achieve the broadband absorption with high efficiency. The absorption caused by the Ir metal layer deposited on the bottom of PAA and the funneled light into the alumina absorbed within the Ir film covering the inner sidewalls, both contribute the broadband absorption of the proposed absorber. This novel absorber can be implemented in fields of solar cell, light harvesting, imaging and so forth.

10112-38, Session 9

Ultrafast coherent dynamics of excitons, phonons, and plasmons in two-dimensional (2D) materials and devices *(Invited Paper)*

Farhan Rana, Haining Wang, Jared H. Strait, Cornell Univ. (United States)

Two-dimensional atomically thin materials, most notably graphene and transition metal dichalcogenides (TMDs), have generated tremendous interest among researchers. The high electron mobility and strong light absorption exhibited by these materials make them attractive for opto-electronic applications. We will present our recent experimental and theoretical work on the ultrafast dynamics of collective excitations, such as excitons, phonons, and plasmons, in these materials for electronic and photonic device applications.

We study the dynamics of excitons in 2D materials and optoelectronic devices using ultrafast optical/terahertz pump-probe and correlation spectroscopy. Our experimental work on metal dichalcogenide materials and devices (such as photodetectors) as well as our theoretical results show that defect assisted recombination involving capture of excitons and carriers by Auger scattering is the fastest mechanism for the non-radiative recombination of photoexcited electrons and holes. In particular, the very Coulomb interaction that resulted in the strongly bound excitons in these materials, causes extremely fast capture of the excitons by defects resulting in extremely poor quantum efficiencies in optoelectronic devices. The large sensitivity of device performance to defects is thus fundamental to 2D TMD materials. Defect-passivated 2D materials have demonstrated quantum efficiencies approaching ten percent. Our ultrafast two-pulse photovoltage correlation experiments show that the photoresponse of TMD photodetectors can be very fast making them useful for operation at frequencies in the hundreds of gigahertz range.

Our recent experimental work has shown that 2D materials could be very promising for high frequency phononic devices. Our work has shown that mechanical oscillations in these atomically thin membranes can reach terahertz frequencies and are tunable from few tens of gigahertz to almost one terahertz. 2D material membranes can therefore enable MEMs resonator structures with record frequency-quality factor products at these high frequencies.

Our ultrafast work in graphene plasmonic structures has revealed enormous potential for graphene based VLSI interconnects in which electrical signals are carried by plasmonic waves with much reduced propagation delays, losses, signal distortions, and cross-talk compared to conventional metal interconnects like copper.

10112-39, Session 9

Plasmonics-enhanced broadband graphene photodetector

Semih Cakmakyapan, Mona Jarrahi, Univ. of California, Los Angeles (United States)

Graphene is a promising two-dimensional material for photo-detection owing to its high mobility, broadband optical absorption, zero band gap nature, and tunable carrier concentration through electrical gating. Despite these unique properties, its 2.3% optical absorption from ultraviolet to infrared wavelengths and short carrier lifetime has limited its usage for practical applications. In this work, we present a broadband, high responsivity, and high speed graphene photodetector. By use of plasmonic nanoantennas, an incident optical field can be strongly concentrated in close proximity to the metallic nanoantennas. This significantly reduces the drift path length of the majority of photo-generated carriers in graphene to the plasmonic nanoantennas that serve as the photodetector contact electrodes. As a result, a large number of the photo-generated carriers can drift to the photodetector contact electrodes despite the short carrier lifetime of graphene, offering high responsivity levels. Moreover, the photodetector is designed to offer high speed operation by minimizing the capacitive parasitics induced by the plasmonic nanoantennas. We demonstrate a broadband photo-detection operation covering the wavelength regime from 800 nm to 1800 nm. We achieve responsivity levels as high as 0.6 A/W at 800 nm, which is close to the theoretical limit of 0.65 A/W. In summary, the combination of the high-responsivity, broad bandwidth, and high-speed performance of the presented plasmonics-enhanced graphene photodetector could find many applications in future optical communication, imaging and sensing systems.

10112-40, Session 9

Strong light enhancement and confinement in two-dimensional transition metal dichalcogenides

Hossein Taghinejad, Mohammad Taghinejad, Hamed Mousavi, Tianren Fan, Ali A. Eftekhar, Ali Adibi, Georgia Institute of Technology (United States)

No Abstract Available

10112-41, Session 9

Light-matter interaction in 2D material heterostructures

Tianren Fan, Hossein Taghinejad, Ali A. Eftekhar, Ali Adibi, Georgia Institute of Technology (United States)

Two-dimensional transition metal dichalcogenide (TMDC) heterostructures provide a unique platform for strong light-matter interaction in a wide wavelength range. Here, we report the formation of high-quality TMDC heterostructures through a dry transfer method along with the study of the detailed physical properties of heterostructures formed between MoS2 and MoSe2 (especially, simultaneous quenching of photoluminescence of both materials in the overlapping region, red shift and broadening of the MoSe2 photoluminescence) will be reported. We also report the formation of a thin tunable diode by depositing metal contacts on TMDCs and the back-gate.

10112-89, Session 9

All-diamond metasurface mirror for high-power laser applications

Haig Atikian, Harvard Univ. (United States); Pawel M. Latawiec, Harvard School of Engineering and Applied Sciences (United States); Xiao Xiong, Harvard Univ. (United States); Marko Loncar, Harvard School of Engineering and Applied Sciences (United States)

In the presence of high intensity laser fields, typical optical components based on multilayer thin-film coatings are subject to unavoidable laser induced damage primarily due to the constituting materials of these optical components. Imperfections in the coating layers, or at the interfaces between the layers, form sites where laser energy can be absorbed, thus generating a tremendous amount of heat. Diamond exhibits many favorable material properties for optical applications. In particular, it has a relatively high refractive index (2.4), a wide bandgap (5.5eV), and a large optical transmission range from the UV into the mid infrared. Further, diamond is particularly attractive as a material for high power lasers in the visible to mid infrared range due to its excellent optical transmission properties and astonishingly high thermal conductivity at room temperature (2200W/mK). We present a novel advancement, where a nanostructured diamond surface can be designed to have wavelength selectivity for a given bandwidth and become a perfect dielectric mirror. The fact that the device is made

completely from bulk diamond, which is the highest thermal conductivity material, one can realize optical elements with extremely high laser induced damage thresholds (LIDT). We have characterized our mirror to have ~99% reflectivity around 1064nm, and measured its LIDT to a continuous wave 1064nm laser to 225MW/cm2 with no damage, orders of magnitude higher than commercially available high energy mirrors.

10112-42, Session 10

Electrical tuning of optical antennas *(Invited Paper)*

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

The scaling of active photonic devices to deep-submicron length-scales has been hampered by the fundamental law of diffraction and the absence of materials with sufficiently strong electrooptic effects. Here, we demonstrate a solid state electro-optical switching mechanism that can operate in the visible spectral range with an active volume that is well below the free-space diffraction limit and comparable to the size of the smallest active electronic components. . The switching mechanism relies on electrochemically displacing atoms inside the nanometer-scale gap between two crossed metallic wires forming a crosspoint junction. Such junctions afford extreme light concentration and display singular optical behavior upon formation of a conductive channel. We illustrate how this effect can be used to actively tune the resonances of a plasmonic antenna. The tuning mechanism is analyzed using a combination of electrical and optical measurements as well as electron energy loss (EELS) in a scanning transmission electron microscope (STEM).

10112-43, Session 10

Optical trapping with plasmonic and photonic nanostructures *(Invited Paper)*

Kenneth B. Crozier, The Univ. of Melbourne (Australia)

The development of integrated approaches for optical trapping, based on photonic or plasmonic structures fabricated on a chip, offers several compelling advantages. First, chip-based optical traps enable the trapping platform to be miniaturized. Second, the chip-based configuration lends itself naturally to the incorporation of sensing modalities. Third, optical nanostructures can generate strong near-fields, boosting the trapping performance.

In this presentation, works by the author and his team in the field of optical trapping with silicon photonics and with plasmonics are described. We will describe the use of silicon microring resonators for trapping and sensing particles. We will furthermore describe silicon photonics for sorting particles, as well as for sensing proteins. Finally, we will describe experiments in which a silicon photonic crystal cavity trapped a silver nanoparticle on whose surface molecules had been formed. We carried out Raman spectroscopy of these molecules, with the silver nanoparticle held in position via the photonic crystal cavity.

Plasmonic nanostructures are compelling for optical trapping due to the large gradient forces they can generate, a consequence of their ability to generate highly confined optical fields. Yet deleterious thermal effects can also occur. We describe the use of a plasmonic nanotweezer with an integrated heat-sink. If time permits, we will also describe recent work in which fluorescence microscopy was used to track the position of a nanoparticle trapped by a double nanohole aperture.

10112-44, Session 10

Full RGB liquid-crystal-tunable plasmonic color and TFT integration

Daniel Franklin, Debashis Chanda, Univ. of Central Florida (United States)

Plasmonic color originating from metallic nanostructures has many advantages over traditional pigmentation based color and have demonstrated sub wavelength resolution, tolerance to high intensity light, and scalability of the structure's optical response with dimensions and surrounding media. The later of these attributes, post-fabrication tunability, is a unique advantage of plasmonic structures that may enable it to reach niche applications. However, previous attempts of plasmonic tuning have yet to span an entire color space with a single nanostructure dimension. Here, we demonstrate a full red-green-blue (RGB) color changing surface enabled by a high birefringent liquid crystal (LC) and with a single nanostructure. This is achieved through the onset of a surface roughness induced polarization dependence and a combination of bulk and surface LC effects which manifest at different voltages. To further show the feasibility of such a system for display applications, we integrate the LC-plasmonic device with an actively addressed thin film transistor array (TFT) to display arbitrary images and video. Such a color changing surface may also find applications in wearables and active camouflage.

10112-45, Session 10

High-contrast structural colour printing with arrays of plasmonic nano antennas

Renilkumar Mudachathi, RIKEN (Japan); Takuo Tanaka, RIKEN (Japan) and RIKEN Ctr. for Advanced Photonics (Japan) and Tokyo Institute of Technology (Japan)

Plasmonics have been actively explored for the structural colour printing applications owing to their preferential photon absorption and scattering. To date, many schemes have been demonstrated for the realization of full colour pixels employing various plasmonic geometries. However the quest for a perfect plasmonic geometry that offers pure colour pixels with distinct reflective peaks and high colour saturation combined with low cost and high throughput scalable fabrication is not yet fulfilled. We propose a scheme for generating all colours from violet to red in the visible spectrum with high colour purity and saturation by a clever engineering of concomitant multiple plasmonic resonances in 2D arrays of aluminum based nano antennas.

In order to realize vivid full colour pixels, we fabricated 2D arrays of aluminum nano squares raised on top of PMMA nano posts in the back ground of a perforated back reflector by systematically varying the square size (D) and periodicity (P). In the single layer fabrication process the PMMA nano posts were defined by electron beam lithography and subsequently aluminum thin film was deposited by thermal evaporation to form both the nano squares and the fishnet like back reflector. The colour formation is based on the excitation of plasmonic light absorption at two distinct wavelengths leaving a central reflective peak that is coherently scattered by coupling to a strongly radiating dipole resonance. Pure colours both in the RGB and CMY colour schemes with extreme reflective peaks of high quality factor (FWHM of 100nm) across the visible spectrum are demonstrated.

10112-46, Session 10

Plasmonic optical nanotweezers

Rehab K. Ali, Mentor Graphics Egypt (Egypt) and The American Univ. in Cairo (Egypt); Mahmoud El Maklizi, The American Univ. in Cairo (Egypt); Yehea Ismail, The Ctr. for Nanoelectronics and Devices, The American Univ. in Cairo (Egypt) and Zewail City of Science and Technology

(Egypt); Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

Plasmonic grating structures can be used in many applications such as nanolithography and optical trapping. In this paper, we used plasmonic grating as optical tweezers to trap and manipulate dielectric nano-particles. Different plasmonic grating structures with single, double, and triple slits have been investigated and analyzed. The three configurations are optimized and compared to find the best candidate to trap and manipulate nanoparticles. The three optimized structures results in capability to super focusing and beaming the light effectively beyond the diffraction limit. A high transverse gradient optical force is obtained using the triple slit configuration that managed to significantly enhance the field and its gradient. Therefore, it has been chosen as an efficient optical tweezers. This structure managed to trap sub10nm particles efficiently. The resultant 50KT potential well traps the nano particles stably. The proposed structure is used also to manipulate the nano-particles by simply changing the angle of the incident light. We managed to control the movement of nano particle over an area of (5μm x 5μm) precisely. The proposed structure has the advantage of trapping and manipulating the particles outside the structure (not inside the structure such as the most proposed optical tweezers). As a result, it can be used in many applications such as drug delivery and biomedical analysis

10112-47, Session 11

Tuning harmonics with electronics: Voltage controlled nonlinear optics in nanostructured metals *(Invited Paper)*

Wenshan Cai, Georgia Institute of Technology (United States)

Metallic nanostructures have offered not only the exciting opportunity to manipulate light waves in unconventional manners, but also the exciting potential to create customized nonlinear media with tailored high-order effects. Two particularly compelling directions of current interests are active plasmonics, where the optical properties can be purposely manipulated by external stimuli, and nonlinear plasmonics, which enable intensity-dependent frequency conversion of light. By exploring the interaction of these two directions, we leverage the electrical and optical functions simultaneously supported in nanostructured metals and demonstrate electrically-controlled nonlinear processes from plasmonic metamaterials. We show that a variety of nonlinear optical phenomena, including the wave mixing and the optical rectification, can be purposely modulated by applied voltage signals. In addition, electrically-induced and voltage-controlled nonlinear effects facilitate us to demonstrate the backward phase matching in a negative index material, a long standing prediction in nonlinear metamaterials. Other results to be covered in this talk include photon-drag effect in plasmonic metamaterials and ion-assisted nonlinear effects from plasmonic crystals in electrolytes. Our results reveal a grand opportunity to exploit plasmonic metamaterials as self-contained, dynamic electrooptic systems with intrinsically embedded electrical functions and optical nonlinearities for signal generation, information processing, and biochemical sensing.

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10112-48, Session 11

Optical security features and filters using plasmonic nanostructures

Benjamin Gallinet, Fabian Lütolf, Luc Dümpelmann, Guillaume Basset, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Angélique Luu-Dinh, Ctr Suisse d'Electronique et de Microtechnique SA (Switzerland); Marc Schnieper, Christian Bosshard, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

The interaction of light with metallic structures at the nanoscale generates strong plasmonic color effects in the visible and near infrared range. The fabrication of plasmonic nanostructures using ultra-violet (UV) imprint and thin metallic coatings is reported. Aluminum and silver are used as plasmonic materials. Wafer-scale manufacturing and process compatibility with cost-efficient roll-to-roll production are demonstrated, which paves the road towards an industrial implementation. With this method, tilted nanolamellas are fabricated and show a strong color variations as a function of the viewing angle, with application in anticounterfeiting and optical security for document protection. A similar method is applied to generate plasmonic filters with deep sub-wavelength features. As they do not suffer from dispersion, they can be easily used in high numerical aperture optical systems and detectors. The embossing of flexible structures finally allows to use these plasmonic systems as color sensors of mechanical constraint.

10112-49, Session 11

How to get rid of diffractive orders and harmonics in total absorbing nanoantennas

Patrick Bouchon, Paul Chevalier, Julien Jaeck, ONERA (France); Fabrice Pardo, Ctr. de Nanosciences et de Nanotechnologies (France); Riad Haïdar, ONERA (France)

Optical nanoantennas are building blocks to design absorbing surfaces, or equivalently near unity emissivity surface, with applications in photodetection, solar cells design, biochemical sensors and thermal emitters.

In most of these applications, a large area of absorbing surface is required thus leading to assembly of nanoantennas, and the direct way to design this assembly is to use a periodic distribution.

However, such an assembly is plagued by the diffraction orders appearing at angles of incidence set by the periodicity, and a strong coupling between has been evidenced between the diffractive orders and the antenna mode which is detrimental to the absorption efficiency.

A first design is based on a perturbation of a periodic arrangement, leading to a significant reduction of the radiative losses. Then, a random assembly of nanoantennas is built following a Poisson-disk distribution of given density, in order to obtain a nearly perfect cluttered assembly with optical properties of a homogeneous material [1]

Harmonics resonance can also deteriorate the performances of devices. For instance, the efficiency of a thermal source is decreased when energy is sent to spectral bands which are not of interest. In the last part of the presentation, nanoantennas that are not presenting harmonics resonances will be investigated [2].

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10112-50, Session 11

Geometrically-induced loss suppression in plasmoelectronic nanostructures

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Nanostructured metals have utilized the strong spatial confinement of surface plasmon polaritons to harness enormous energy densities on their surfaces, and have demonstrated vast potential for the future of nano-optical systems and devices. While the spectral location of the plasmonic resonance can be tailored with relative ease, the control over the spectral linewidth associated with loss represents a more daunting task. In general, plasmonic resonances typically exhibit a spectral linewidth of ~50 nm, limited largely by the combined damping and radiative loss in nanometallic structures. Here, we present one of the sharpest resonance features demonstrated by any plasmonic system reported to date by introducing dark plasmonic modes in diatomic gratings. Each duty cycle of the diatomic grating consists of two nonequivalent metallic stripes, and the asymmetric design leads to the excitation of a dark plasmonic mode under normal incidence. The dark plasmonic mode in our structure, occurring at a prescribed wavelength of ~840 nm, features an ultra-narrow spectral linewidth of about 5 nm, which represents a small fraction of the value commonly seen in typical plasmonic resonances. We leverage the dark plasmonic mode in the metallic nanostructure and demonstrate a resonance enhanced plasmoelectric effect, where the photon-induced electric potential generated in the grating is shown to follow the resonance behavior in the spectral domain. The light concentrating ability of dark plasmonic modes in conjunction with the ultra-sharp resonance feature at a relatively low loss offers a novel route to enhanced light-matter interactions with high spectral sensitivity for diverse applications.

10112-51, Session 11

Angle robust reflection/transmission plasmonic filters based on ultrathin metal patch array

Chenying Yang, Weidong Shen, Yueguang Zhang, Xu Liu, Zhejiang Univ. (China)

A new omnidirectional plasmonic filter using ultrathin metal patch array structure is proposed. The plasmonic filters can be used as reflective RGB filters as well as transmissive CMY filters simultaneously and can present the same perceived reflection/transmission color at unpolarized illumination for a broad range of incidence angles. The reflection/transmission curves are coincident at different angles and the color difference characterized by CIE DE2000 formula is inconceivably small, implying that no color variation can be observed for a large angle up to 60 degree. Various colors can be obtained by simply tuning the dimension of the patch structure. The simulated reflectance/transmittance and electric field distribution profile of the plasmonic filter was performed by Finite-Difference Time-Domain (FDTD) method. And the color devices were fabricated by steps of sputtering deposition and focus ion beam (FIB) milling, which could be replaced by the nanoimprint technique as well as the column fabrication method based on the porous anodic alumina (PAA) template and atomic layer deposition technique to greatly reduce preparation time and cost. The measured results agree well with the simulated results, confirming the unique characteristic of this structure. The localized surface plasmonic resonance excited within the single metallic patch is responsible for the angle insensitive color filtering feature of this plasmonic filter. And because of this, patch array with as few as two periods were sufficient to demonstrate color filtering. This method, described in this paper, can have tremendous potential for various applications in the fields of display, detecting, printing, decoration and so forth.

10112-52, Session 11

Fabrication and optimization of ITO-Ag co-sputtered nanocomposite films as plasmonic materials in the near-infrared region

Chaonan Chen, Hui Ye, Zhejiang Univ. (China)

Systematic study of magnetron sputtered silver-indium tin oxide (Ag-ITO) composite films has been carried out by altering the volume ratio of silver in the co-sputtered films. Films with thickness of 200 nm are fabricated under identical experimental conditions. The optimal micro-structure characteristic with smooth surface and tight junction between silver and ITO particles could be obtained by tuning Ag volume fraction. Lower resistivity of the fabricated device is realized with the decrease of silver volume ratio, which can be explained by ultra-high mobility in films with less silver content, verified by Hall measurement. After rapid thermal annealing process, the electrical properties are greatly increased, comparable with those of our best ITO films under more rigorous conditions (1.5?10-4 ?·cm). In addition, spectroscopic ellipsometry is applied in order to evaluate the plasmonic properties. Real and imaginary permittivity of the films are retrieved utilizing Drude-Lorentz dispersion model. The cross-over wavelength of the films, optimized to as low as 936 nm, exhibits high adjustability on the ratio of silver material. And much lower imaginary permittivity as well as tunable real permittivity suggest the potentiality of Ag-ITO nanocomposite films as substituted plasmonic materials in the near-infrared region. Moreover, Ag-ITO films can present much better bendability than that of the pure ITO film through fold testing, which provides a new potential application of the Ag-ITO films for flexible plasmonics.

10112-70, Session PWed

Enhancing the emission directionality of phosphor with a grating-nanobelt structure

Akira Hashiya, Yasuhisa Inada, Mitsuru Nitta, Shogo Tomita, Taku Hirasawa, Panasonic Corp. (Japan)

Controlling the directionality and polarization of light sources plays an important role in many optoelectronic devices such as displays, lighting and projectors. We have developed a technique for controlling the emission characteristics of luminescent material by modifying it into nanostructured waveguide. In our previous work, we reported that the resonant emission of a nanograting waveguide phosphor can be controlled by tuning the dimension and the geometry of the nanograting for a designated wavelength. This structure, however, also shows the resonant emission at wider angle for the wavelength away from the designated wavelength.

In this presentation, we have developed a grating nanobelt structure to enhance the directionality of broadband visible emission. The grating nanobelt is based on the ridge waveguide with a nanograting on top. In this structure, the wider-angle resonant modes are suppressed for the following reasons: 1) The belt structure only supports the waveguide modes which propagate parallel to the nanobelt. 2) Only the TE modes are supported while the TM modes are cut-off due to the thickness of the nanobelt. To fabricate the samples, we deposited YAG:Ce phosphor onto the one dimensional nanograting followed by a lift-off process. We have demonstrated the directional emission within 20 degrees for the wavelength of 500-700 nm. We also show that the angle-dependence of the resonant modes agrees with our simulations.

10112-71, Session PWed

Optical and plasmonic devices in the infrared using ion-implanted semiconductors

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Recently, highly doped semiconductors have been explored as "metal-like" alternatives for noble metals in various plasmonic devices at infrared frequencies. Unlike noble metals, the carrier concentration of semiconductors can be engineered across many orders of magnitude, resulting in a wide and tunable range of plasma frequencies spanning the mid-infrared and terahertz ranges.

In this work, we fabricate micron-scale 2D and 3D mid-infrared photonic and plasmonic devices embedded in silicon, using ion implantation through lithographically defined masks to locally control the free carrier concentration. We demonstrate diffractive optical elements including Fresnel zone plates and diffraction gratings, as well as plasmonic devices such as frequency selective surfaces and gratings that couple to surface plasmon polaritons. The optical properties of silicon with various implantation conditions and doping profiles were measured by spectroscopic ellipsometry, with crossover wavelengths reaching approximately 4 ?m and doping concentrations near 1 x1021 cm-3. We use finite-difference time-domain calculations and ion-stopping simulations to validate our designs.

Our process creates completely planar and monolithic devices that are robust against high temperatures and physical erosion, and can be easily integrated into other CMOS platforms.

10112-72, Session PWed

Optical characteristics plasmonic LEDs with and without dielectic films

Shohei Matsuo, Meijo Univ. (Japan)

Efficient light sources emitting the three primary colors (red, green and blue) are indispensable to create full color and white light with high color rendering. Development of efficient blue and red LEDs has already been succeeded. However, the green LED still has lower emission efficiency because of the high-density defects and quantum-confined Stark effect caused by a high piezoelectric field. The enhancement of radiative recombination rate by the surface plasmon resonance in neighboring Ag nanoparticles is a potential solution to realize an efficient green LED. In such devices, the distance between the active layer and Ag nanoparticles should be small to keep the planmon resonance. Too thin p-GaN layer, however, reduces electron confinement in the active layer, and the LED performance must be degraded. Therefore, the optimal thickness of p-GaN layer has to be used for realization of efficient green LEDs. In addition, dielectric film inserted between LED and Ag nanoparticle may also enhance the plasmon resonance.

In this presentation, the performance of GaN-based plasmonic green LEDs with a variation of p-GaN layer thickness were investigated. The Ag nanoparticles were formed on the surface of p-GaN layer. The LED with the p-GaN layer thickness of 100 nm has the highest output power, which is 3.6 times higher than that of the device without plasmonic effect. The effect of the insertion of SiO2 dielectric film between the p-GaN layer and Ag nanoparticle will also be discussed at the presentation.

10112-74, Session PWed

Observation of indirect-to-direct bandgap transition in nanomesh of molybdenum disulfide (MoS2)

Chan Ho Choi, Yeungnam Univ. (Korea, Republic of); Jihun Mun, Sang-Woo Kang, Tae Wan Kim, Korea Research Institute of Standards and Science (Korea, Republic of); Jae Cheol Shin, Yeungnam Univ. (Korea, Republic of)

Next two-dimensional (2D) materials beyond graphene have been desired due to its zero bandgap drawbacks. Transition metal dichalcogenides (TMDs) such as MoS2 and WSe2 are the potential candidates for next 2D materials since atomically thin layers of TMDs exhibit very unique and versatile electrical and optical properties. Although bulk TMDs materials reveal an indirect bandgap nature, indirect-to-direct bandgap transition is observed in monolayer of TMDs (MoS2, WSe2, MoSe2) [1-3]. The synthesis of the large scale monolayer of TMDs using chemical vapor deposition (CVD), however, is very difficult due to controlling of the highly uniform atomic monolayer. Here, we demonstrate the nano-patterned bulk MoS2 materials which is fabricated by using an aluminum oxide membrane (AAO) template. We note that the nano-patterned bulk MoS2 exhibits a direct bandgap optical transition. More importantly, the bandgap energy of the nano-patterned bulk MoS2 can be tuned by changing of the nano-hole size. The AAO template has been widely used to provide large scale nano-patterned structures. The hole size of the AAO template was tuned from 20 nm to 250 nm. The morphological and optical properties of the nano-patterned bulk MoS2 materials was examined with a scanning electron microscopy (SEM), atomic force microscope (AFM), and a photoluminescence spectrum measurement. The electrical properties of the nano-patterned bulk MoS2 is further characterized by fabricating back-gate transistor.

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10112-75, Session PWed

Silver-decorated silicon nanowires array as surface-enhanced Raman scattering (SERS) substrate

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Raman scattering is an excellent analysis tool because a wealth of information can be obtained using a single measurement. It can also be configured as a diagnostic tool as a label free sensing method. In that case, enhancing the Raman signal is important to improve the sensitivity and detect low concentrations of analytes. Finite Difference Time Domain simulations showed that a range of enhancement factors is possible up to 10^9, making the method promising for single molecule detection. A nanoparticle showing a particular Raman enhancement shows a much higher enhancement when it is on a nanowire. This was also confirmed experimentally. We report on a simple fabrication method of silver nanoparticles and silicon nanowires decorated with these nanoparticles. The nanowires were fabricated using metal assisted chemical etching using HF and AgNO3 followed by nitric acid. The nanoparticles were deposited also using HF and AgNO3 in different concentrations. Samples were then immersed in Pyridine of different concentrations for 1 hour. An enhancement factor of around 6 to 8?10^5 was observed for silver nanoparticles alone. By depositing the same nanoparticles on silicon nanowires, the enhancement factor jumped 10-fold to 7?10^6.

10112-76, Session PWed

Design and fabrication of photonic crystal superlens for mid-infrared telescopes

Naofumi Fujishiro, Kyoto Sangyo Univ. (Japan)

We are developing a photonic crystal superlens based on negative refraction effect for mid-infrared astronomical telescopes to improve their angular resolution. The superlens will convert incident beams of large F-number to output beams of small F-number without changing image height. Firstly, we designed the superlens by theoretical calculations. We optimized two-dimensional dielectric structures of the superlens by calculating its band structures and iso-frequency contours using Plane-wave expansion (PWE) method. We also studied interface structures of input/output ports of the superlens in order to maximize its transmittance by numerical calculations using Fourier modal method (FMM). Then, wave-propagation simulations through the superlens by Finite-difference time-domain (FDTD) method showed that Full Width Half Maximum (FWHM) of point spread function will be reduced by approximately half. Secondly, we are trying to manufacture the superlens using a three-dimensional laser lithography system based on two-photon polymerization process. We also have measured complex refractive indices of SU-8 photoresist around wavelength of 10 micron by spectroscopic ellipsometry. The fabrication and optical benchmark of the superlens are currently underway. In this paper, we present experimental results as well as the design process of the superlens.

10112-77, Session PWed

Ultra-sensitive molecular detection using surface-enhanced Raman scattering on periodic metal-dielectric nanostructures

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Surface-enhanced Raman scattering (SERS) is a powerful technique for trace chemical analysis and single molecule detection in the application of biochemical monitoring and food safety due to its ability to enhance the Raman scattering of molecules near the metallic surface or nanostructures.

Here, we present a comprehensive study of the SERS enhancement by the periodically nanostructured surface, where the thin film of silver is deposited onto the surface, except the sidewall of posts, of 1-D lamellar gratings with varying pitch to forming metal-dielectric composite nanostructures. By enhancing the localized and surface-propagating mode in the vicinity of the concaves, the SERS signal can be improved by amplifying the intensity of electric field and increasing the optical path length of the incident light. Both numerical and experimental investigations show that the enhancement factor can be manipulated by varying the polarization of incident light and the pitch size of gratings.

To demonstrate the SERS effects of the proposed structures, thin layers of benzoic acid, which is commonly used as a food preservative, are deposited on the SERS substrates by spin-coating a solution of benzoic acid and dried at room temperature. A Confocal Raman microscope with a 532 nm laser source is used to illuminate light and measure the Raman spectrum of benzoic acid. We demonstrate the Raman signal of benzoic acid can be enhanced on the order of 10^2 on the SERS substrates. We anticipate that our results will enable applications such as label-free detection of molecules and biosensing.

10112-79, Session PWed

Design of self-assembled aluminum-oxide nanowire arrays for perfect absorber

Kyuyoung Bae, Kyoungsik Kim, Yonsei Univ. (Korea, Republic of)

Nanowire structures made of dielectric and metal materials have received considerable interest in many research field for nanoelectronic, photonic, and optoelectronic applications. Dielectric nanowires have been extensively studied due to the multiple scattering of light between the nanowires, and metal or metal-dielectric nanowires are also exploited for the extinction by surface plasmon resonance. In this study, we demonstrate self-assembled aluminum oxide (SAO) nanowire arrays with gold deposition for broadband perfect absorbers. The SAO nanowire arrays are fabricated by a conventional anodizing, chemical etching, and drying process. The SAO nanowires are aggregated in funnel shape by capillary force during the drying process and formed ridge-and-valley shape in the whole area. The array structure can be controlled by a length and diameter of the nanowires and they exhibit different optical properties. After gold is deposited on the arrays, broadband absorption is emerged due to the plasmonic nanofocusing along the nanowires. The SAO nanowire arrays shows an efficient absorption in the range from UV to NIR wavelength. Multiple light scattering induced by the nanowires and plasmonic nanofocusing by nanogap between the nanowires can facilitate the strong light absorption. The design of gold-coated SAO nanowire arrays are of large importance for the nanowire-based devices.

10112-80, Session PWed

Enhanced cavity-waveguide interaction in three-dimensional photonic crystals

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In this study, we propose a drop-out mechanism based on the enhanced interaction between a defect waveguide and defect microcavities in three-dimensional chirped woodpile photonic crystals (WPCs). We first show that light can be gradually slowed down in the defect waveguide (WG), which is obtained by gradually changing the period of the surrounding WPC along the propagation direction. In result, the waveguide mode gradually approaches the band edge region, while this phenomenon has three consequences. First, the Fourier components of propagating wave will be spatially separated as each frequency will reach its zero velocity at different positions [1]. Second, as the wave slows down, it will penetrate deeper into the surrounding cladding, thus increasing the coupling efficiency between the WG and a nearby placed resonator. Third, the high density of states near the band edge result in highly efficient light scattering of a nearby placed resonator, which in turn increases the quality factor of the interaction [2]. Following this idea, the acceptor type cavities, which are tuned to the localized frequencies, are side-coupled to the WG at respective wave localization areas. Furthermore, drop channels have been introduced to read-out the trapped spectra, showing that the targeted frequencies can be detected selectively. Compared to previous studies, our approach has the advantages of low radiation losses, the absence of any reflection feedback and both enhanced quality factor and transmission of the captured light.

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10112-81, Session PWed

Electromagnetic field analysis of the gap plasmonic resonance with metal-dielectric-metal nanoparticles

Minjung Choi, Kyoungsik Kim, Yonsei Univ. (Korea, Republic of)

Ultrathin film absorbers using gap plasmonic resonance (GPR), requires highly detailed spatial electromagnetic field analysis, which have already been performed for metal-dielectric-metal (MDM) structures with metal disks, and cuboids. Here, we conducted careful spatial electromagnetic field distribution analysis for MDM structure, consisting of the bottom metallic reflector layer, nanoscale dielectric spacer, and top metallic hemispherical nanoparticles (HSNPs), because the HSNPs of few tens of nanometer-sized diameter are easy to fabricate through thermal dewetting, in large scale without lithography. MDM structure allows strong confinement of electromagnetic fields inside the nanometer-sized dielectric spacer by exciting GPR. In this scheme, the top metallic layer of HSNPs controls localized surface plasmon resonance (LSPR) and Fabry-Perot-like GPR behaviors. While the bottom reflector reflects the incident light as a mirror, the dielectric spacer can act as ultrathin absorber by building a constructive interferential surface plasmonic standing wave within the spacer. We performed 3D full-field electromagnetic simulations (FDTD solution, Lumerical Solutions, Inc.) for a domain containing a single HSNP in the center on top of stacked aluminum oxide spacer-gold reflector on a substrate. We considered 7 nm of space between the HSNP and the 300-nm thick reflector by an ultrathin aluminum oxide spacer. Numerically acquired electromagnetic field profile describe a particular nature of excited LSPR mode with a strong electric field at the HSNP edges and an excited circular electric current, which induces enhanced magnetic field within the spacer layer. These are noteworthy GPR features that explain GPR can be supported by HSNPs with MDM structure.

10112-82, Session PWed

Dual-mode MOS SOI nanoscale transistor serving as a building block for optical communication between blocks

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Silicon-based light-emitting devices are highly desirable for the realization of integrated optical signal processing with electronic data processing. This is in correlation with the efforts to develop a generation of ultrafast processors based on the combination of electronic and optical signal processing and on advanced generations of optoelectronic devices for optical communication systems.

If many types of silicon photo-activated devices were developed, silicon emitting devices were found more difficult to realize. This is in tandem with efforts to develop new generation of ultra-fast computers based on combined electronic and optical signal processing on one hand, and advanced generations of optoelectronic devices for optical communication systems on the other hand.

A new device based on Silicon-On-Insulator (SOI) starting material technology, and Gate-Recessed-Channel (GRC) technique have been designed, and largely simulated with Comsol and Matlab SW packages. First generation of devices has been processed and tested. The obtained quantum structure enable light emission under controlled conditions The model presents several expected values of energy levels which can enable light emitting mechanism.

10112-83, Session PWed

Photonic crystal nanobeams on a biodegradable substrate

Sejeong Kim, Yong-Hoon Cho, KAIST (Korea, Republic of)

Consumer electronics are not only purchased by every individual but are often replaced by newly released models. The short lifetimes of electronic devices cause environmental problem, as semiconductors in discarded electronics are not degradable and are sometimes even toxic. As an alternative solution, green electronics of using bio-degradable substrate instead of typical bulk silicon is proposed. Successful performances of electronic devices with partially replaced by bio-degradable materials are demonstrated.

Because electronic devices are expected to reach limitations soon in terms of bandwidth and integratability, photonic devices have attracted much attention by virtue of their ability to handle massive amount of data. Photonic circuits are expected gradually to replace electronics in the future. In consequence, the photonic devices will also encounter environmental issue due to discarded semiconductors.

Here, we report a semiconductor photonic crystal nanocavity on a paper substrate. When considered teh refractive index of paper at 1. 55 um, the simulation result showed that the nanocavity on paper has a Q-factor of 48,000. This nanocavity showed lasing action, which is the first observation of a photonic cevice operating directly on papser. We additionally observed the wavelength shift when water infiltrated into cellulose fiber, indicating that this device can be utilized as a sensor. Semiconductor optical cavities combined with a paper substrate pave the way for eco-friendly, sustainable, and mass-producible photonic devices which could reduce the cost of high-tech devices.

10112-84, Session PWed

Utilizing microsphere-based enhanced-intensity laser ablation for nanopatterning polymers

Akshit Peer, Iowa State Univ. of Science and Technology (United States) and Ames Lab. (United States); Rana Biswas, Ames Lab. (United States) and Iowa State Univ. of Science and Technology (United States)

Nanopatterned polymers play an important role in various devices such as solar cells, LEDs, metal-coated plasmonic structures and in biological experiments such as tissue culture and cell growth. We use rigorous scattering matrix simulations to demonstrate a pathway to develop nanopatterns on polymer surfaces coated with glass nano/micro spheres. When polymer surfaces coated with periodic microspheres in a close packed lattice are irradiated with a laser of desired wavelength and power, the electric field intensity beneath the spheres is enhanced by an order of magnitude, generating enough heat to ablate nanometer-size regions of the material, in a periodic array. The array of glass spheres can be self-assembled on any curved or flat surface, and these spheres can be utilized as an optical lens to focus light energy within the surface. We investigate a typical prototypical organic biodegradable polymer poly-L-lactic acid (PPLA) having refractive index of ~1.55 in visible regime. There is high transmission through 150 μm thick PLLA substrate which exceeds ~90% over much of the optical spectrum >400nm. We have examined different sizes of microspheres with diameters ranging from 100nm-1.3μm. The simulated

electric field intensity within the PLLA substrate for 1.3μm spheres shows that light can be focused into small regions 150-300 nm below the surface where the light intensity is dramatically enhanced by a factor >12. This suggests that high intensity pulsed lasers may be able to ablate cylindrically shaped pits in the surface of the polymer to a depth of 100 nm–needed for the patterning application.

10112-85, Session PWed

Dispersion engineering in mid-infrared region for hybrid plasmonic waveguide using semiconductors

Abdalrahman A. Abdelhamid, Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

The dispersion properties of a hybrid plasmonic waveguide in the mid-infrared region (3-10 μm) are studied and engineered. The hybrid plasmonic waveguides have proved to have the best compromise between propagation length and power confinement in comparison to other plasmonic waveguides. III-V semiconductor materials were chosen to build the waveguide under interest. The same materials were used to build the quantum cascade lasers in this wavelength range, which opens the door for integration of the waveguide and the laser in the same technology. The waveguide is built using GaAs as the substrate, AlAs as the low index core and doped InAs as the plasmonic material. The dispersion curve was engineered by changing the waveguide dimensions, and the doping level of the InAs. We used doping levels ranging from 5E19 cm-3 to 2.5E20 cm-3, and dimensions ranging from 150 nm to 4 um for the width of the waveguide, 150 nm to 3 um for the height of the cladding, and 10 nm to 100 nm for the height of the core. Several observations were made. First, both negative and positive dispersion were observed. Second, the doping level and the core height controls the slope of the negative dispersion. Third, varying the doping level or the core height shifts the dispersion curve with respect to the wavelength axis. Fourth, the width and height of the waveguide controls the effective index. Hybrid plasmonic waveguide based on semiconductor materials can be used as an electrical or optical switch in the mid-infrared region.

10112-86, Session PWed

UV sensing behavior of Li-doped ZnO nanocrystalline films synthesized by sol-gel spin coating method

Chung-Yuan Kung, National Chung Hsing Univ. (Taiwan); San-Lin Young, Hsiuping Univ. of Science and Technology (Taiwan)

Transparent Zn1-xLixO (x=0.01, 0.02, 0.04 and 0.08) nanocrystalline films were prepared by a simply sol-gel spin coating method followed by thermal annealing treatment. Li doping effect on the microstructural and optical properties of the Zn1-xLixO films is investigated. From FE-SEM images of all films, a progressive decrease of the uniform grains with increasing Li doping is observed. X-ray diffraction measurements of the films show the same wurtzite hexagonal structure and preferential orientation along the c-axis. Mean grain size decreases from 29.8 nm for x=0.01, 20.1 nm for x=0.02, 19.5 nm for x=0.04 to 16.1 nm for x=0.08 deduced from the XRD patterns. Transmittance spectra of the films reveal a decrease of transmission with increasing Li doping. Photoluminescence spectra of the films show a strong ultraviolet (UV) emission and a weak visible (Vis) light emission peak. An increase of Vis/UV emission intensity ratio is observed due to the increase of Li doping concentration and the corresponding increase of oxygen vacancy defects. Finally, the characteristics of the dark and illuminated currents with (p-Zn1-xLixO film)/(n-Si substrate) heterojunction structure are studied for UV photodetector application. Current-voltage (I-V) curves were measured in the dark (Idark) and under UV illumination (Iphoto) with applied bias from -5V to 5V. The current variation, defined as (Iphoto-Idark)/Idark, at 5 V increases from 9.86 for x=0.01, 17.32 for x=0.02, 40.95 for x=0.04, to 149.55 for x=0.08, respectively. From the I-V curves, the results reveal an obvious enhancement in the responsivity of the device which illustrates the possibility for the UV photodetection application.

10112-87, Session PWed

Far-field and near-field analysis of localized and propagating plasmons on opalic metallic surfaces

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Engineering the density of states is a major issue in nanophotonics for manipulating the interaction between light and matter. For an opalic plasmonic sample, realized by deposition of a thick gold layer on an opal, the mixing of hexagonal sphere periodic arrangement and singularities between spheres makes it possible to excite on a wide spectral range of both localized and propagating surface plasmons on large surface. The versatility of such system is evidenced in the context of two complementary experiments, specular reflective spectrometry and photoemission electron microscopy (PEEM), which highlight the different mechanisms implied in plasmon excitation. Under low power laser excitation, resonant plasmonic excitation is evidenced by specular optical spectroscopy, whereas PEEM experiment requires high power laser for achieving non resonant plasmon excitation. Moreover the electronic density mapped by PEEM experiment demonstrate as well interference fringes associated to propagating plasmons as the presence of high intensity hot spots. Coupling between propagating and localized plasmons is demonstrated. We discuss the modifications of emission for single molecules or nanocrystals deposited at the singularities between metallic spheres. Such experiments evidence the opportunities offered by these 2D materials in the context of nanophotonics.

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10112-88, Session PWed

Periodic nanostructural materials for nanoplasmonics

Dukhyun Choi, Kyung Hee Univ. (Korea, Republic of) and Yonsei Univ. (Korea, Republic of)

Nanoscale periodic material design and fabrication are essentially fundamental requirement for basic scientific researches and industrial applications of nano-science and engineering. Innovative, effective, reproducible, large-area uniform, tunable and robust nanostructure/material syntheses are still challenging. Here, I would like to introduce the novel periodic nanostructural materials particularly with uniformly ordered nanoporous or nanoflower structures, which fabricated by simple, cost-effective, and high-throughput wet chemical methods. We also

report large-area periodic plasmonic nanostructures based on template-based nanolithography. The surface morphology and optical properties are characterized by SEM and UV-vis. spectroscopy. Furthermore, their enhancement factor is evaluated by using SERS signals.

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10112-53, Session 12

Quantum nanophotonics: from inverse design to implementations *(Invited Paper)*

Jelena Vuckovic, Stanford Univ. (United States)

By completely opening the parameter space in design of nanophotonic circuits, new functionalities and better performance relative to traditional optoelectronics approaches can be achieved. We have recently developed an inverse (objective first) approach to design nanophotonic structures only based on their desired performance. Moreover, constraints including structure robustness, fabrication error, and minimum feature sizes can be incorporated in design, without need to have an optics expert as a designer. Finally, such structures are fully fabricable using modern lithography and nanofabrication techniques. We have also demonstrated devices designed using this approach, including ultra-compact and efficient wavelength splitters on the silicon platform. Beyond integrated photonics, this approach can also be applied to design of quantum photonic circuits.

10112-54, Session 12

Nanophotonic structures for topological photonics and quantum light sources *(Invited Paper)*

Ganapathi S. Subramania, P. Duke Anderson, Arthur J. Fischer, Daniel D. Koleske, Sandia National Labs. (United States)

A significant fraction of future optical communications will involve transport of quantum information. To that end there is an increasing interest in exploring nanophotonic structures for quantum light sources (e.g. single photon sources) and topological photonics. Single photon sources are useful as sources for transmitting units of quantum information (qubits). On the other hand topological photonic structures are important for lossless manipulation of such photonic qubits. They operate by exploiting nanophotonic structures with unique dispersion properties that offer topological protection resulting from either by explicit breaking or preservation of time-reversal symmetry for photon transport. In this talk, we will present recent research carried out in our group at Sandia National laboratories in these areas. In particular, we will discuss III-nitride based architectures for room temperature single photon sources as well as structures for topologically protected light transport at optical frequencies.

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10112-55, Session 12

Ultrafast non-equilibrium dynamics of hot electrons in plasmonic nanoparticles

Imran Hossain, Ahmet A. Yanik, Univ. of California, Santa Cruz (United States)

More recently, novel photovoltaic approaches based on extraction of hot electrons created by non-radiative decay of surface plasmons in metallic nanostructures and nano-antennas have taken much attention. Utilization of hot electrons offer high efficiency photovoltaic devices with a spectral responses that are not limited by the band gap of the semiconductors. Although proof of concept realization of these hot-electron devices are demonstrated, the reported hot-electron extraction efficiencies remain to be too low for any practical applications (<%0.01). There is a lack of understanding why the efficiencies are so low given the theoretical estimates above %10 are reported. In this proceeding, we introduce a bottom-up quantum electron transport model of hot-electron dynamics and current in plasmonic nano-antennas. Our quantum mechanical approach is based on non-equilibrium Green's function (NEGF) formalism, which has been shown to be a unified, extremely efficient and accurate way to explain quantum transport and design nanoscale electronic devices. By merging our quantum mechanical transport approach with ultrafast and non-equilibrium energy transfer processes in metallic particles, we unravel ultrafast plasmon decay dynamics and introduce design parameters to achieve high efficiency photodiodes and potentially solar cells at room temperature.

10112-56, Session 12

Surface plasmon dispersion engineering by using TiN/Au double metallic layers for yellow up to red spectral emitters

Yiming Zhong, Ioannis Fragkos, Nelson Tansu, Lehigh Univ. (United States)

The challenges in achieving high efficiency InGaN-based quantum well (QW) light-emitting diodes (LEDs) in the yellow-amber-red spectral regimes are attributed to the low radiative recombination rate and poor material quality from this active region alloy containing high Indium content. The use of surface-plasmon coupled active region to increase the photon density of states had been demonstrated in the blue and green spectral regime. Specifically, the use of Ag layer and Au/Ag double layers for increasing the Purcell factors of InGaN QWs in blue and green spectral regimes had been demonstrated.

In this work, we investigate the physics and design for surface plasmon structures applicable for achieving high Purcell factors in InGaN QW coupled active region for yellow-amber-red spectral emissions. The use of TiN / Au double metallic layer was found as attractive for enabling high Purcell factors across large range of emission wavelength in the ~580 nm up to 620 nm. The structure of TiN / Au double metallic layers allows the tuning of surface plasmon dispersion between that of TiN and Au, which provides the optimum Purcell factor tuning in the wavelength of interest where the InGaN QW active region has low internal quantum efficiency. The use of such surface plasmon coupled QWs had been demonstrated to result in an order-magnitude of enhancement in the green-emitting InGaN QWs. The use of TiN / Au based structure is expected to result in Purcell factors in the order of ~ 100 over the yellow up to red spectral regimes.

10112-57, Session 12

Fluorescence from unusually-shaped gold nanoparticles

Thomas A. Klar, Dmitry Sivun, Cynthia Vidal, Johannes Kepler Univ. Linz (Austria); Dong Wang, Peter Schaaf, Technische Univ. Ilmenau (Germany); Battulga Munkhbat, Nikita Arnold, Calin Hrelescu, Johannes Kepler Univ. Linz (Austria)

Bulk gold shows photoluminescence with a negligible quantum yield of only 10-10. However, this yield can be increased by orders of magnitude if gold nanostructures are used.[1] The origin of such fluorescence is given by a multi-step process, where a d-band hole scatters within the d-band to a momentum where it can recombine with an electron from the filled sp-band below the Fermi-level. This leads to the excitation of a plasmon, which can decay radiatively.

We now have found two surprising effects: First, we observed polarized fluorescence only from sponge-like gold nanoparticles below approx. 100 nm in diameter, while larger nanosponges show largely unpolarized fluorescence. In contrast, both large and small nanosponges show highly polarized light scattering.[2] We observe this phenomenon when comparing the scattering and the fluorescence spectra of individual nanosponges of different diameters. Using numerical simulations, we can reproduce this puzzling observation. Second, we fine-tune the tip-to-tip distance of two gold bi-pyramids using AFM manipulation [3] and again take scattering and fluorescence spectra for each individual distance and hence for several hot-spot intensities. We find, that the hot spot intensity anticorrelates with the fluorescence efficiency.

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10112-58, Session 13

Frequency-axis light transport and topological effects in dynamic photonic structures *(Invited Paper)*

Luqi Yuan, Yu Shi, Shanhui Fan, Stanford Univ. (United States)

We study the ring resonator under a dynamic modulation. Each ring resonator supports a set of resonant modes with an equal spacing in the absence of group velocity dispersion. In the case that the modulation frequency is chosen to be close to the frequency spacing, the system can be mapped into a tight-binding model in which each resonant mode corresponds to one lattice site along the frequency axis. This leads to the concept of the synthetic frequency dimension. By controlling the frequency and the phase in the modulator, one can show various physics phenomena along the frequency axis, which are traditionally in the real space.

In details, we show that, by introducing a frequency detuning in the modulation frequency, the system is mapped into a one-dimensional lattice under a constant effective force for photons. It supports a spectral Bloch oscillation along the frequency axis. A periodic switching of the detuning brings out a unidirectional translation of the frequency of light.

Moreover, we consider a one-dimensional array of ring resonators, each of which is dynamically modulated with a different phase. We show that it creates a gauge potential in the synthetic two-dimensional space with the dimensions being the frequency and the spatial axes. Such a gauge potential creates topologically-protected edge states, which could be useful for the generation of higher-order side bands efficiently. Our work therefore points to a new capability for the control of light in the frequency space.

10112-59, Session 13

PT-axisymmetry for extraordinary field confinement

Muriel Botey, Waqas W. Ahmed, Ramon Herrero, Univ. Politècnica de Catalunya (Spain); Kestutis Staliunas, Univ. Politècnica de Catalunya (Spain) and Institució Catalana de Recerca i Estudis Avançats (Spain)

While initially introduced as a curiosity in quantum mechanics [1], Parity-Time (PT-) symmetric systems have found actual realizations in optics, combining index and gain/loss modulations [2,3]. The simplest PT-symmetric 1D optical potential may be taken as: n(x)= n0 exp(iqx), which at resonance, k=q/2 (PT-transition) asymmetrically couples the left-propagating mode, exp(-ikx), to the right-propagating mode exp(ikx), but not vice versa. The question that arises is what happens if such PT-symmetry condition is not met globally, but only locally? Indeed, a complex optical potential in the form: n(x)= n0 [cos(iq?x?) - i sin(iq?x?)] imposes a unidirectional coupling towards a selected position: the P-symmetry center. As a consequence, a strong filed localization may be intuitively expected around x=0. The same idea applies to 2D (or 3D), by radial (or coaxial) dephased modulations of index and gain/loss: n(r) = n0 [cos(iqr)-i sin(iqr)].

Indeed, we explore the spatio-temporal field dynamics of such 1D and 2D complex optical potentials, and find that both systems lead to an extraordinary confinement, a simultaneous field enhancement and localization due to the asymmetric radial coupling of inward and outward waves.

Since the physical realizations of the proposed arrangements are nowadays available, we may expect the effect to find remarkable applications in linear and nonlinear devices requiring a localized high power density. As a possible application, we show the beam quality emission improvement from a 2D PT-axisymmetric VCSEL.

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10112-60, Session 13

Nanoscale electrodynamics of evanescent fields

Daniel B. Fullager, The Univ. of North Carolina at Charlotte (United States)

The well known phenomenon of total internal reflection (TIR) is often seen as a simple index-dependent trapping of light for angles of incidence exceeding the critical angle. Descriptions of the electric field outside the optical component exhibiting TIR are assuredly complex though. The evanescent field surrounding a body exhibiting TIR will couple to other objects with an efficiency determined by the relative distance and optical constants of the bodies in question. This effect can also be enhanced by the use of evanescently coupled resonators. We have analyzed this phenomenon for resonant scatterers exposed to both propagating and evanescent waves in terms of appropriate basis function expansions, some suggesting that all evanescent spatial frequencies and most of their power can be effectively coupled. There is a maximum spatial frequency, k, associated with TIR dependent on the boundary index difference but, for example for objects at some temperature T, there may be no discernable upper bound on k. We describe the design of resonant scatterers that can exchange energy between spatial eigenmodes. We also develop analysis of the trade-off between Q, resonant coupling effectiveness and bandwidth. These methods have obvious applications for heat removal and superresolution imaging.

10112-61, Session 13

Scaling analysis of Anderson localizing optical fibers

Behnam Abaie, Arash Mafi, The Univ. of New Mexico (United States)

Mode area is a measure of transverse size of Anderson localized modes and is calculated using the standard deviation of the normalized intensity distribution of the mode. Mode area probability density function (PDF) is introduced as a powerful tool to study transverse Anderson localization properties of guided modes of disordered optical fibers. The mode area PDF has been used for detailed statistical analysis of the impact of various structural and optical parameters of a disordered fiber. A disordered fiber supports both Anderson localized modes as well as extended modes. The mode area PDF sheds light into the distribution of these modes and provides a powerful framework to manipulate such distributions, for example to quench the number of extended modes while minimally affecting the localized ones. An important observation is the convergence of the mode area PDF to a terminal configuration as a function of the transverse dimension of the disordered fiber. This has been shown by performing a scaling analysis of the mode area PDF and can be quite helpful in turning a formidable computational problem from nearly impossible to a tractable one. Moreover, it is discussed that, depending on the refractive index contrast of random sites in the disordered fiber, and their relative dimensions with respect to optical wavelength, local step-index waveguides can be formed in the disordered structure. Formation of such a local step index waveguides causes discretization of the mode area PDF.

10112-62, Session 14

Optomechanical interaction in locally resonant nanostructures *(Invited Paper)*

Fadi Issam Baida, Vincent Laude Sr., Abderrahmane Belkhir, Mahmoud Addouche, Sarah Benchabane, Abdelkrim Khelif, FEMTO-ST (France)

Nanoscale-engineered optical systems have been thoroughly investigated for a few decades due to their fascinating abilities to confine and enhance electromagnetic fields in very sub-wavelength and have a large number of applications in domains like biosensing, enhanced-Raman spectroscopy, metamaterials, photothermal therapy, and plasmomechanics. In addition, the recent astonishing ability of phononic crystals to control acoustic or elastic waves has been demonstrated. As an elastic wave modulates in time both the shape and the refractive index of the supporting structure, it is possible to influence the optical response of the same system. The purpose of this paper is to investigate, both theoretically and numerically, the coupling between an optical Fano resonant mode and phononic resonances carried within a 2D metamaterial. The latter was designed to exhibit simultaneous phononic and photonic high Q-factor resonances and it is composed of silver slits deposited on a lithium niobate substrate. The phononic properties are first determined and show that several vibration modes can be electrically induced through the specific design of the structure that behaves as an interdigitated transducer. The structure geometries for each mode is then determined over an acoustic period and used to point out the optical transmission modifications when the structure is illuminated at the normal incidence by a linearly polarized plane wave. Original results are obtained for some modes (the first two odd phononic modes) showing a very efficient and non-linear modification of the transmitted intensity. Different operating procedures are then explored by changing the operation optical wavelength value. This study opens the way to the design of a new generation of extremely miniaturized optoacoustic devices.

10112-63, Session 14

RF optical signal processing using microscale phononic crystals *(Invited Paper)*

Charles M. Reinke, Aleem Siddiqui, Sandia National Labs. (United States); Heedeuk Shin, Yale Univ. (United States); Robert L. Jarecki, Andrew L. Starbuck, Sandia National Labs. (United States); Peter T. Rakich, Yale Univ. (United States)

Nano-optomechanical systems (NOMS) that are simultaneously resonant for optical and acoustical modes have to-date facilitated the exploration of fundamental light-matter interactions on the nano-scale and the development of new classes of information processing devices, by leveraging strong coupling of phononic and photonic modes in coupled-cavity configurations. Alternatively, guided-wave optical devices, where non-resonant optical modes interact with resonant phonon modes, are promising for broadband chip-scale radio-frequency (RF) signal processing, such as filtering, time delay, and low-noise stimulated Brillouin scattering (SBS) oscillators. For example, phononic domain filtering allows channel linewidths of 1MHz to be easily achieved, whereas in the optical domain this would require resonators with impractical Q values of 100,000,000 or more. Additionally, sub-wavelength confinement of optical fields in nano-photonic waveguides produces a new regime of SBS, where the strong interaction of light with the boundaries of a nano-scale waveguide radically enhances SBS for suitably chosen geometries through the coherent combination of optical forces arising from electrostriction and radiation pressure.

In this talk, results on devices enabled by photon-phonon interactions in NOMS devices will be presented. Measurements of a second-order RF filter will be shown, demonstrating an unrivaled combination of dynamic range, bandwidth, and wavelength insensitivity. Also, large signal delay devices enhanced by propagating phonons that greatly exceed what can be achieved using light alone will be discussed.

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10112-64, Session 14

New horizons in the manipulation of GHz-THz acoustic nanowaves

Fabrice Lamberti, Carmen Gomez Carbonell, Loïc Lanco, Olivier Krebs, Ctr. de Nanosciences et de Nanotechnologies (France) and Ctr. National de la Recherche Scientifique (France); Bernard Jusserand, Institut des NanoSciences de Paris (France); Pascale Senellart, Aristide Lemaître, Norberto D. Lanzillotti-Kimura, Ctr. de Nanosciences et de Nanotechnologies (France) and Ctr. National de la Recherche Scientifique (France)

The development of micro- and nanofabrication techniques enabled the study of nanostructures where it is possible to engineer the acoustic phonon dynamics –acoustic waves with nanometric wavelengths and frequencies in the GHz-THz range–. In these structures it is also possible to engineer the photonic properties and control both the dynamics and the interactions between the photonic and phononic fields. High resolution Raman scattering gives direct access to the phonon dynamics in the frequency domain, and to the spatial distribution of strain in nanostructures.

In this presentation we will introduce new strategies to engineer and study semiconductor nanostructures capable of confining, controlling the propagation, and manipulating acoustic phonons in the GHz-THz frequency range. Superlattices work as high reflectance phononic mirrors

and constitute a fundamental building block for the conception of more complex devices. Acoustic cavities are capable of confining and amplifying the acoustic field both spatially and in the spectral domains. Usually, an acoustic cavity is formed by two identical distributed Bragg reflectors embedding an acoustic spacer, acting in a similar way to a Fabry-Perot resonator. We design a novel kind of phononic cavities where no spacer is needed, based on the engineering of the phonon phase at the interface between two superlattices. Such kind of resonators are combined with optical microcavities, allowing the signal enhancement in Raman scattering experiments. We experimentally demonstrate these novel phonon-confinement strategies and simulate the results using a photoelastic model.

10112-65, Session 14

Electrical modulation and switching of acoustic phonons

Young-Dahl Jho, Gwangju Institute of Science and Technology (Korea, Republic of); Hoonil Jeong, Korea Photonics Technology Institute (Korea, Republic of); Christopher J. Stanton, Univ. of Florida (United States); Dong-Sean Lee, Minyeo Kim, Gwangju Institute of Science and Technology (Korea, Republic of)

We report on electrically modulating and switching the wavy properties of acoustic phonons in nanoscale piezoelectric heterostructures which are strained both from the pseudomorphic growth at the interfaces as well as through external electric fields. In symmetry planes of such structures, the generation and detection of the transverse acoustic modes are forbidden, and only longitudinal acoustic phonons are generated by ultrafast displacive screening of strains. We show that the combined application of lateral and vertical electric fields can not only turn on and off various modes but they can also modulate the amplitudes and frequencies of the modes [1-3]. The role of the electrical controllability of phonons was further demonstrated as changes to the propagation velocities; the electrically polarized TA waves; and the geometrically varying optical sensitivities of phonons. The capability to manipulate the phononic functionalities with electric fields is analogous to that for manipulating photons and electrons in major technological devices and can be a practical route for integrated phononic circuitry.

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10112-66, Session 15

Coherent on-chip optical memory: storing amplitude and phase as acoustic phonons *(Invited Paper)*

Benjamin J. Eggleton, Birgit Stiller, Moritz Merklein, The Univ. of Sydney (Australia)

We demonstrate for the first time the storage of multiple phase and amplitude levels of an optical signal as coherent acoustic phonons. The storage concept is implemented on-chip with a GHz-bandwidth.

10112-67, Session 15

Magneto-phononic nanostructures *(Invited Paper)*

Cassidy Berk, Mike Jaris, Weigang Yang, Univ. of California, Santa Cruz (United States); Stefano Cabrini, The Molecular Foundry (United States); Holger Schmidt, Univ. of California, Santa Cruz (United States)

Magnetic and mechanical resonances can show strong interplay in patterned nanomagnet arrays. We review these phenomena and discuss methods of controlling the influence of surface acoustic waves on nanomagnet dynamics.

10112-68, Session 15

Cavity optomechanics in silicon-on-insulator

Christopher J. Sarabalis, Jeff T. Hill, Amir H. Safavi-Naeini, Stanford Univ. (United States)

The optical and mechanical properties of silicon and silica glass make the silicon-on-insulator material system a platform natural for photonics and challenging for phononics. High index-contrast enables index-guiding in silicon waveguides on glass, but silicon's relative stiffness and high sound velocity hampers analogous efforts to ``index-guide'' acoustic waves. Waveguide geometry plays fundamentally different roles in the dispersion of mechanical and optical waves, enabling radiation-free waveguiding in high aspect-ratio cantilevers defined in silicon. We fabricate silicon fins, here 80 nm wide in 340 nm SOI, that exhibit low-loss mechanical resonances at 600-700 MHz.

We present designs, numerical studies, and the first measurements of release-free optomechanical "fin cavities" in 340 nm SOI. The dispersion of flexural fin mechanical modes is readily engineered by variation of the fin's width. TE and TM optical cavities at telecom frequencies are made with an adjoined nanobeam. Nanobeam geometry independently influences the optics decoupling optical and mechanical design problems. Optical and mechanical modes can be colocalized with a simple cavity where a parabolically curved fin is placed near a photonic crystal waveguide. We simulate and measure optical and mechanical spectra of these devices. Optomechanical interaction rates ranging from low kHz to 500 kHz for the fin cavities are demonstrated. Furthermore, by analyzing the interaction rates we identify the different optical modes of these structures. The demonstrated SOI fin cavities create new opportunities for quantum optomechanical sensing in a truly CMOS-compatible setting.

10112-69, Session 15

Laser-induced phonon-phonon interactions in an on-chip silicon optomechanical crystal

Rishi N. Patel, Stanford Univ. (United States); Wentao Jiang, Tsinghua Univ. (China) and Stanford Univ. (United States); Zhaoyou Wang, Stanford Univ. (United States) and Tsinghua Univ. (China); Jeff T. Hill, Christopher J. Sarabalis, Amir H. Safavi-Naeini, Stanford Univ. (United States)

Multi-mode optomechanical systems have formed the basis of recent proposals and experiments, enabling optical frequency translation and hybridization of near-resonant mechanical modes. An important question is how to control the internal mechanical states of such systems using laser light. Such control enables engineering of effective nonlinearities for phonons, allowing phonon-phonon frequency translation, mechanical entanglement, and precision metrology. On-chip engineered nanostructures are particularly suitable for exploring multi-mode systems.

Here, we consider a silicon nanobeam optomechanical crystal with two mechanical modes coupled to a common optical mode. Simulations of the phonon-phonon scattering parameters of the system suggest that large conversion efficiency can be obtained at cryogenic temperatures. We show that remarkably, phonon-phonon conversion efficiency near unity is achievable, even when the loss rate of the intermediate optical mode dominates all other rates in the system by several orders of magnitude. This counter-intuitive phenomenon is the result of a long-lived mechanical dark state of the system that arises in the optical pumping scheme being used. We experimentally demonstrate two GHz frequency mechanical modes, separated by nearly 300 MHz, coupled to a first-order common optical TE mode with vacuum coupling rates of nearly 500 kHz. By optically driving the optomechanical crystal with two tones separated by the mechanical difference frequency we present evidence for optically induced phonon-phonon interactions at room temperature. We will present results of measurements in a cryogenic environment, operating at 4 Kelvin demonstrating improved large phonon-phonon conversion efficiency.

Conference 10113: High Contrast Metastructures VI

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10113-1, Session 1

Comparison of high-contrast grating and photonic crystals: similarities and differences *(Invited Paper)*

Pengfei Qiao, Weijian Yang, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

High contrast grating (HCG) is an emerging element in integrated optics. It is a subwavelength grating with a large refractive index contrast between the grating and the surrounding medium. It has many distinct features not predicted by theories of conventional gratings, such as ultra-high reflectivity or transmission over a broad spectral range and/or various incident beam angles, phase front engineering, and high optical quality factor resonator, etc. The rich and extraordinary properties of HCG in optical wave manipulation as well as its great design intuition and flexibility have attracted a lot of research interests recently.

The HCG is a one-dimensional (1D) periodic structure that are identical to a conventional distributed Bragg reflector (DBR) or 1D photonic crystal. Of course, in essence, all phenomena are solutions of the Maxwell's equations. Nevertheless, the analysis and overarching design principles are distinctly different. For example, both transverse and longitudinal HCGs exhibit similar, extraordinary properties. But for the latter, there is no periodicity projected in the wave vector and the properties were not discovered in photonic crystals or conventional gratings. In this talk, we will discuss some of the similarities and differences in the analytical formulation which leads to intuitive designs and understandings.

10113-2, Session 1

High-index dielectric optical metasurfaces with broken vertical symmetry *(Invited Paper)*

Pierre Viktorovitch, Univ. de Lyon (France) and Institut des Nanotechnologies de Lyon (France); Florian Dubois, Univ. de Lyon (France); Thierry Deschamps, Hai Son Nguyen, Xavier Letartre, Jean-Louis Leclercq, Institut des Nanotechnologies de Lyon (France); Christian Seassal, Institut des Nanotechnologies de Lyon (France)

The seminal work of R.B. Wood (1902), who discovered anomalies in the reflection spectra of sub-wavelength metallic gratings, triggered the field of plasmonics, where ultra-thin metallic sheets laterally structured on a sub-wavelength scale, so called metallic meta-surface, are under operation. The goal of the field has extended considerably in the last decades and has aimed at arbitrary control over the amplitude, phase and polarization... of light waves at the sub-wavelength scale. All-dielectric meta-surfaces consisting in nano-structured thin films of high index dielectric material, are attracting much attention, owing to their capability to achieve the same goal as their metallic counterpart, yet with an enhanced efficiency (especially for the manipulation of strong optical resonances), being freed from significant energy dissipation as encountered in metallic nano-structures. All dielectric meta-surfaces have been around for quite a while, but were named differently (photonic crystal dielectric membranes or high index contrast gratings). Unless rare exceptions, the literature reports on structures with non-broken vertical symmetry. In the present contribution we emphasize that breaking the vertical symmetry of all-dielectric meta-surfaces provides a widely enhanced degree of freedom for the control of spatial routes and spectral characteristics of light, which depends, to an essential extent, on the local density of photonic states in the thin nano-structured dielectric film. As an enlightening illustration, we concentrate on a dielectric meta-surface formed by two super-imposed identical evanescently coupled gratings, with adjustable gap distance and lateral alignment. We show that this remarkably simple meta-surface can provide any local density of photonic states from zero (Dirac cone) to infinity (ultra-flat zero curvature dispersion characteristics), as well as any constant density over an adjustable spectral range. Exemplifying applications will illustrate the great potential of this new approach.

10113-3, Session 1

Structured light-matter interactions in engineered optical media *(Invited Paper)*

Natalia M. Litchinitser, Jingbo Sun, Mikhail I. Shalaev, Wiktor T. Walasik, Pei Miao, Zhifeng Zhang, The State Univ. of New York (United States); Stefano Longhi, Politecnico di Milano (Italy) and Istituto di Fotonica e Nanotecnologie (Italy); Liang Feng, The State Univ. of New York (United States)

Structured light and structured matter are two fascinating branches of modern optics that recently started having a significant impact on each other. However, integrating structured light, which commonly is created using bulk optics, on miniaturized silicon chips represents a significant challenge. In this talk, we discuss fundamental optical phenomena at the interface of structured light and engineered optical structures, including theoretical and experimental studies of light-matter interactions of vector and singular optical beams in optical metamaterials and microcavities. The synergy of complex beams, such as the beams carrying an orbital angular momentum (OAM), with nanostructured "engineered" media is likely to bring new dimensions to the science and applications of structured light ranging from fundamentally new regimes of spin-orbit interaction to novel ways of information encoding for the future optical communication systems.

We show that unique optical properties of engineered micro- and nanosctructures open unlimited prospects to "engineer" light itself. We discuss several approaches to ultra-compact structured light wavefront shaping using metal-dielectric and all-dielectric resonant metasurfaces. Moreover, by exploiting the emerging non-Hermitian photonics design at an exceptional point, we demonstrate a microring laser generating a single-mode OAM vortex lasing with the ability to precisely define the topological charge of the OAM mode. We show that the polarization associated with OAM lasing can be further manipulated on demand, creating a radially polarized vortex emission. Our OAM microlaser could find applications in the next generation of integrated optoelectronic devices for optical communications in both quantum and classical regimes.

10113-4, Session 1

Addressing nanoantennas with slow Bloch mode cavity: application to optical trapping

Laurent Milord, Cécile Jamois, Xavier Letartre, Pierre Viktorovitch, Institut des Nanotechnologies de Lyon (France); Ali El Eter, Thierry Grosjean, Fadi Issam Baida, FEMTO-ST (France); Taha Benyattou, Institut des Nanotechnologies de Lyon (France)

Photonic crystal and plasmonic structures are the two main approaches used in nanophotonic for efficiently confining and enhancing the electromagnetic field at subwavelength scale. For these reasons, these two approaches have been both used for the optical trapping of nanometric particle. We present, here, experimental results showing that structures combining both photonic crystal and nanoantennas could lead to improved trapping performances.

In previous theoretical papers [1, 2] we have shown that when the critical coupling between a photonic crystal and a nanoantenna is reached, a large Gaussian beam could be efficiently coupled to a single nanoantenna. In this way, it is possible to generate a nanometric hotspot in the nanoantenna leading to a very efficient optical trap.

The experimental demonstration of this effect has been obtained on an SOI sample consisting in a gold nanoantenna located at the centre of a photonic crystal cavity. Stable trapping of 100 nm diameter nanoparticle has been observed using a 5mW laser at 1.31µm with a 5µm waist. The nanoparticle are trapped above the nanoantenna gap and a normalized trap stiffness of 0.3 fN.nm-1.mW-1 is measured. This result demonstrates the interest of this approach. We will discuss and compare it to the state of the art of nanotweezers.

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10113-5, Session 2

Dielectric metasurface-based freeform optics *(Invited Paper)*

Arka Majumdar, Univ. of Washington (United States)

The macroscopic volume of optical sensors, such as cameras, often originates from the requirement of having multiple optical elements and thick spherical geometries. In recent years, researchers have made subwavelength optical elements, commonly known as metasurfaces, with an ultra-thin form factor using well-developed semiconductor nano-fabrication technology. In parallel with the progress in such nano-photonic devices, researchers have also made vast improvements in the field of freeform optics. Freeform optics aim to expand the toolkit of optical elements beyond those exhibiting rotational symmetry. Most conventional optical elements have rotational symmetry for manufacturing reasons, but freeform optics emphasizes complex surface geometries, which are difficult to manufacture by traditional means. While both metasurface and freeform optics have progressed substantially in recent years, they have developed independently of one another as their respective research communities are fairly disconnected. In my talk, I will show how metasurface technology is ideal for the realization of subwavelength scale freefrom optics, with applications in implantable bio-sensing and potentially in augmented reality systems. I will present some of our recent results on metasurface freeform optics that enable a large depth of focus and a tunable focal length lens.

10113-6, Session 2

Recent progress in semiconductor nanowire photodetectors for color and multispectral imaging *(Invited Paper)*

Kenneth B. Crozier, The Univ. of Melbourne (Australia)

We present recent studies in which engineering the interaction between light and nanoscale materials has been pursued for applications in image sensors and in spectroscopy. In the first, we present recent work by the author and colleagues on the use of silicon [1-5] and germanium [6] nanowires for multispectral imaging. We show that their ability to support waveguide modes leads to spectrally-selective absorption properties [1]. We show that this in turn enables the nanowires to be used as filters or photodetectors for color and multispectral imaging [2-6].

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[6] A. Solanki and K. B. Crozier, Appl. Phys. Lett. 105, 191115 (2014)

10113-7, Session 2

Device applications of metafilms and metasurfaces

Mark L. 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 demonstrate how one can improve the performance of such devices by nano-structuring the constituent layers at length scales below the wavelength of light. The resulting metafilms and metasurfaces offer opportunities to dramatically modify the optical transmission, absorption, reflection, and refraction properties of device layers. This is accomplished by encoding the optical response of nanoscale resonant building blocks into the effective properties of the films and surfaces. To illustrate these points, I will show how nanopatterned metal and semiconductor layers may be used to enhance the performance of solar cells, photodetectors, and enable new imaging technologies. I will also demonstrate how the use of active nanoscale building blocks can facilitate the creation of active metafilm devices.

10113-8, Session 2

CMOS-compatible zero-index metamaterial

Yang Li, Daryl I. Vulis, Orad Reshef, Philip A. Camayd-Munoz, Mei Yin, Shota Kita, Marko Loncar, Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

Zero-index metamaterials (ZIMs) offer exotic optical properties such as uniform spatial phase and infinite wavelength, as well as photonic applications including super-coupling and omnidirectional phase matching in nonlinear optics.

Here we present an on-chip ZIM consisting of a square array of air-holes in a 220-nm-thick silicon-on-insulator (SOI) wafer. This design enables mass production of ZIM-based photonic devices at low cost and high fidelity using standard CMOS fabrication technology.

To transition from the high-aspect ratio inverse case of silicon pillars under transverse magnetic (TM) polarization, our design is instead intended for a transverse electric (TE) polarization because of TE modes are, in general, better confined than TM modes for a given thin film. Furthermore, the larger volume fraction of silicon provided by the air-holes structure improves the confinement as compared with the silicon-pillars structure. We optimized the design to obtain a zero index corresponding to a finite impedance of 0.8 at 1550 nm. The bandstructure of the metamaterial shows a Dirac-cone dispersion at the center of the Brillouin zone at 1550 nm. These results indicate that this metamaterial possesses an impedance-matched, isotropic zero index at 1550 nm.

To experimentally verify that the metamaterial has a zero index, we fabricated a right-triangular prism measuring twenty unit cells across. The measured effective index of this prism crosses zero linearly at 1630 nm and shows positive and negative indices at short and longer wavelengths, respectively, indicating a Dirac-cone induced zero index. This measurement is in excellent agreement with the result of full-wave simulation.

10113-9, Session 3

The acceleration of electrons with light in nanostructures *(Invited Paper)*

Kenneth J. Leedle, Huiyang Deng, Yu Miao, Jiaqi Jiang, James S. Harris Jr., Stanford Univ. (United States)

High energy particle beams have been foundational elements in physics research the past 7 decades [1] and medical therapy [2]. The acceleration is achieved by high power radio frequency (RF) fields. Unfortunately, their widespread availability is seriously limited by their enormous size and huge cost, creating a strong need for alternatives. Over the past 5 years, a new breed of accelerator nanotechnologists using technologies driven by advances in semiconductor fabrication and "Moore's Law" have now demonstrated several KeV acceleration on micron scale dimensions using high peak power lasers in dielectric nano-structures—a Dielectric Laser Accelerator (DLA)–whose near fields synchronously accelerate charged particles. [4,5,6] To realize a practical "accelerator on a chip", we are developing an integrated system with several crucial elements: dielectric nano-structures serve as phase masks for sustained energy gain, self-focusing structures to keep the beam well collimated and waveguides for efficient energy coupling.

We have demonstrated these essential elements with sub-relativistic electron beams and will describe progress in laser electron acceleration with silicon dual-pillar grating structures with record high acceleration gradients [5] and optically-driven transverse self-focusing of the electron beam [6].

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10113-10, Session 3

Multi-wavelength VCSEL arrays using high-contrast gratings *(Invited Paper)*

Erik Haglund, Johan S. Gustavsson, Chalmers Univ. of Technology (Sweden); Wayne V. Sorin, Hewlett-Packard Labs. (United States); Jörgen Bengtsson, Chalmers Univ. of Technology (Sweden); David Fattal, LEIA Inc. (United States); Åsa Haglund, Chalmers Univ. of Technology (Sweden); Michael Tan, Hewlett-Packard Co. (United States); Anders G. Larsson, Chalmers Univ. of Technology (Sweden)

Wavelength division multiplexing (WDM) can be used to improve the capacity and bandwidth density of optical interconnects. As WDM light sources, multi-wavelength VCSEL arrays are attractive as they may offer performance, efficiency, and cost advantages over other technologies. However, monolithic arrays are intrinsically difficult to realize due to the fact that resonance wavelength of the conventional VCSEL cavity, defined by the spacing between the two distributed Bragg reflectors (DBRs), is set during epitaxial growth. Replacing the top DBR by a high-contrast grating (HCG) enables the resonance wavelength to be set by the grating parameters in a post-epitaxial growth fabrication process, since the phase of the reflection depends on the grating period and duty cycle.

Using this technique, we demonstrate electrically driven monolithic multi-wavelength VCSEL arrays at 980 nm. The VCSELs are GaAs-based and the suspended GaAs HCGs were fabricated using electron-beam lithography, dry etching and selective removal of an InGaP sacrificial layer.

For the resonance wavelength to be sensitive to the phase of the HCG reflection we use an air-coupled cavity design without any additional DBR pairs to boost the reflectivity of the HCG. This requires HCGs with near 100% reflectance. The sub-mA threshold currents and direct reflectivity measurements suggest that the reflectivity of the HCGs is indeed close to 100%. The air-coupled cavity design has enabled 4-channel arrays with 5 nm channel spacing.

10113-11, Session 3

Physical principles of monolithic high-contrast gratings

Maciej Dems, Lodz Univ. of Technology (Poland)

The thick multi-layered Bragg mirrors in surface-emitting lasers can be replaced with subwavelength High-Contrast Gratings (HCGs) only a few-hundred nanometers thick, which—if properly designed—can reflect 100% of the incident light. Such gratings are composed of parallel high-refractive-index bars separated by air gaps and arranged periodically with a pitch smaller than the incident light wavelength. Conventionally, it has been assumed that HCGs must be surrounded on both the top and bottom sides by a low-refractive-index material, such as air or an oxide. However, we have recently demonstrated subwavelength Monolithic HCGs (MHCGs), in which the low-refractive-index layer on one side is replaced by a layer with high refractive index. Such MHCGs are still equally as good as classical HCG mirrors.

Although MHCGs support multiple diffraction orders of the reflected wave, they show no scattering: all the energy is reflected into the zero diffraction order. This effect is the key factor enabling application of MHCGs in VCSELs. Without it, the scattering losses would dominate significantly over the laser gain and would make lasing impossible.

In the talk, I explain this phenomenon. I present visually the results of a numerical analysis of the transition between classical HCGs and MHCGs and I identify the source of the differences between the scatter-less reflection peaks and those that either show strong scattering or do not occur in MHCGs. I show that the key property of MHCGs is a very special form of the grating's impedance/admittance matrix, which causes the zero-order reflectivity peak to be independent of the substrate refractive index. This form of matrix can be obtained for any wavelength and in almost any material system by tuning the geometrical parameters of the grating—its pitch, fill-factor, and height.

10113-12, Session 3

Design and fabrication of sub-wavelength gratings in 10um wavelength range

Brian R. Hogan, Stephen P. Hegarty, Liam Lewis, Cork Institute of Technology (Ireland) and Tyndall National Institute (Ireland); Javier R. Vivas, Cork Institute of Technology (Ireland); Tomasz J. Ochalski, Guillaume Huyet, Cork Institute of Technology (Ireland) and Tyndall National Institute (Ireland)

The emergence of sub-wavelength gratings has allowed for enhanced performance of optical elements such as broadband reflectors, narrow line filters and polarisers. Up to now such elements have focused mainly on telecommunications applications. However, there remains a broader range of applications such as gas detection, breath analysis and bio-sensing which can be enhanced by these sub-wavelength gratings. This work enables these new applications to be realised.

To achieve functional operation in these applications, the gratings need to be capable of operating at wavelengths of 10μm and greater. This presents a challenge to the current state of the art as the most widely used grating materials, silicon and silicon dioxide, suffer from loss at these wavelengths. Here we propose a new combination of materials which have been used to design and fabricate a grating capable of functioning as a broadband reflector at operational wavelengths of 10 μm and beyond. We also demonstrate numerically that these materials, when designed as a broadband reflector, exhibit a high reflectivity ($R>0.99$) bandwidth of 3.02μm around a central wavelength of 10μm.

Furthermore, we detail the fabrication process which has used to realise these gratings. Significantly, this fabrication process is not reliant on the use of e-beam lithography but instead uses standard UV/DUV lithography. This simplifies the fabrication process even further and reduces lead times for fabrication. Characterisation of our sub-wavelength gratings show strong agreement between theoretically predicted and experimentally measured results.

10113-13, Session 3

Optimization of VCSELs incorporating monolithic subwavelength high-refractive-index contrast surface grating mirrors

Marcin Gebski, Maciej Dems, Lodz Univ. of Technology (Poland); Philip Moser, James A. Lott, Technische Univ. Berlin (Germany); Tomasz G. Czyszanowski, Lodz Univ. of Technology (Poland)

We present results of computer simulations of vertical-cavity surface-emitting lasers (VCSELs) incorporating monolithic high refractive index contrast gratings (MHCGs). In typical VCSELs, two thick multilayer distributed Bragg reflectors (DBRs) are used as top and bottom mirrors. A typical VCSEL is 25-lambda or more in optical thickness and composed of more than a hundred epitaxial layers, while the VCSEL's active region can be as optically-thin as a half-lambda. In order to decrease the number of epitaxial layers and the total thickness of the VCSEL, we replace all or part of the top DBR with an MHCG mirror, which provides very high reflectivity for the desired emission wavelength at a particular polarization. The MHCG is made of a single epitaxial material layer, and it can be patterned on a surface of any preferably nonabsorbing material that has a real refractive index higher than 1.75. The MHCG opens a new way to manufacture InP- and GaN-based VCSELs by eliminating the DBRs. . In our design, the MHCG is used as a top reflector in state-of-the-art 980-nm GaAs VCSELs that are optimized for high-speed optical data communication. We present results of simulations of several different designs of MHCG VCSELs via a fully self-consistent numerical model that incorporates electrical, thermal, gain, current diffusion, and optical modules. We discuss the impact on VCSEL performance of different oxide-aperture diameters, tunnel junction apertures, the number of grating stripes, alternative grating patterns, and the number of DBR mirror periods added to our monolithic surface grating.

10113-14, Session 4

Metalenses at visible wavelengths: an historical fresco *(Invited Paper)*

Philippe Lalanne, Lab. Photonique, Numérique et Nanosciences (LP2N), IOGS - Univ. Bordeaux, CNRS (France); Pierre H. Chavel, Lab. Charles Fabry (France)

Since the publication of a research article in Science that revisited Snell's law at the interface between two uniform media thanks to an ultrathin metallic grating etched on the interface, metasurfaces and especially metalenses, are the subject of an intense research activity, leading to numerous publications in high-impact journals and great promizes. A recent research article [Khorasaninejad et al., Science 352, 1190 (2016)] that reports record diffraction efficiency from a high numerical aperture (NA) metalens operating at visible wavelengths is particularly emblematic of this craze. Comparisons with a state-of-the-art commercial objective suggest that the image quality is as good and even better, and considering their flat nature and compact size, metalenses appear as potentially revolutionary. However, metalenses do not come out of the blue and the so-called 'flat optics' that shapes the phase of free-space waves through subwavelength structures have a venerable history over many years from the microwave domain down to the visible. What is the paradigm change at the source of this anticipated revolution? New fabrication processes, new concepts, new applications, fundamental limitation shifts?

To answer these questions, now is the time to confront recent metalens achievements with a historical perspective of flat optical elements, to further analyze the fundamental limitations that have been lifted (if any) and better anticipate future perspectives offered by flat optics.

10113-15, Session 4

Planar lenses at visible wavelengths for high-end optics *(Invited Paper)*

Mohammadreza Khorasaninejad, Wei Ting Chen, Alexander Y. Zhu, Jaewon Oh, Robert C. Devlin, Charles Roques-Carmes, Ishan Mishra, Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

We present a new platform that realizes high performance metasurfaces in the visible spectrum. This platform is based on atomic layer deposition of titanium dioxide and allows molding incident light wavefront to desired shapes including holographic images, optical vortices, and Bessel beams. The focus of this work will be on the design and demonstration of planar metalenses. We report on our recent experimental realization of high numerical aperture metalenses with efficiency as high as 86%. These metalenses can focus light into a diffraction-limited spot and can be employed for imaging purposes to provide sub-wavelength imaging resolution. In addition, by the judicious design of metalens building blocks, one can achieve a multispectral chiral metalens (MCML) within a single metasurface layer. The MCML can simultaneously resolve chiral and spectral information of an object without the requirement of additional optical components such as polarizers, wave-plates, or even gratings. Using this MCML, we map the chiroptical properties of a macroscopic chiral biological specimen across the visible range. Finally, since many applications require polarization insensitive planar lenses, we discuss the experimental realization of such metalenses with numerical apertures as high as NA=0.85. These metalenses can focus incident light to a spot as small as ~0.6lambda with efficiencies up to 70%. The straightforward and CMOS-compatible fabrication process of this platform is promising for a wide range of optics-based applications in multidisciplinary science and technology.

10113-16, Session 4

Planar optical components and systems based on dielectric metasurfaces *(Invited Paper)*

Amir Arbabi, Ehsan Arbabi, Seyedeh Mahsa Kamali, Yu Horie, Andrei Faraon, California Institute of Technology (United States)

Miniaturized optical systems with planar form factors and low power consumption have many applications in wearable and mobile electronics, health monitoring devices, and as integral parts of medical and industrial equipment. Flat optical devices based on dielectric metasurfaces introduce a new approach for realization of such systems at low cost using conventional nanofabrication techniques. In this talk, I will present a summary of our recent work on dielectric metasurfaces that enable precise control of both polarization and phase with large transmission and high spatial resolution. Optical metasurface components such as high numerical aperture lenses, efficient wave plates, components with novel functionalities, and their potential applications will be discussed. I will also present the results of our efforts on developing multi-wavelength and dispersion engineered metasurfaces, as well as conformal, flexible, and tunable metasurfaces. Furthermore, by using metasurface cameras and planar retroreflectors as examples, I will introduce a vertical on-chip integration platform enabled by vertical stacking of multiple metasurfaces and active optoelectronic components. This vertical integration scheme introduces a new architecture for the on-chip integration of conventional and novel optical systems and enables their low-cost manufacturing.

10113-17, Session 5

All-dielectric high-contrast metasurfaces for polarization diversity and mode-shaping *(Invited Paper)*

Uriel Levy, Meir Grajower, Jonathan Bar David, Boris Desiatov, Noa Mazurski, The Hebrew Univ. of Jerusalem (Israel)

Dielectric metasurfaces are shown to be useful for variety of applications in flat optics geometry. Here, we demonstrate our recent work on dielectric metasurfaces in silicon for applications such as polarization selectivity and beam shaping. Different design and performance metrics will be presented.

10113-18, Session 5

Visible light metasurfaces based on single-crystal silicon *(Invited Paper)*

Jonathan A. Fan, Jianji Yang, David Sell, Sage Doshay, Kai Zhang, Stanford Univ. (United States)

Semiconducting nanostructures are promising as components in high performance metasurfaces. We show that single crystal silicon can be used to realize efficient metasurface devices across the entire visible spectrum, ranging from 480 to 700 nanometers. Alternative forms of silicon, such as polycrystalline and amorphous silicon, suffer from higher absorption losses and do not yield efficient metasurfaces across this wavelength range. To demonstrate, we theoretically and experimentally characterize the resonant scattering peaks of individual single crystal silicon nanoridges. In addition, we design high efficiency meta-gratings and lenses based on nanoridge arrays, operating at visible wavelengths, using a stochastic optimization approach. We find that at wavelengths where single crystal silicon is effectively lossless, devices based on high aspect ratio nanostructures are optimal. These devices possess efficiencies similar to those made of titanium oxide, which is an established material for high efficiency visible wavelength metasurfaces. At blue wavelengths, where single crystal silicon exhibits absorption losses, optimal devices are instead based on coupled low aspect ratio resonant nanostructures and are able to provide reasonably high efficiencies. We envision that crystalline silicon metasurfaces will enable compact optical systems spanning the full visible spectrum.

10113-19, Session 5

Increasing efficiency of high-NA metasurface lenses

Amir Arbabi, Ehsan Arbabi, Seyedeh Mahsa Kamali, Yu Horie, California Institute of Technology (United States); Seunghoon Han, California Institute of Technology (United States) and SAMSUNG Semiconductor, Inc (Korea, Republic of); Andrei Faraon, California Institute of Technology (United States)

Diffractive optical devices based on dielectric metasurfaces have recently attracted significant attention. Small size, low weight, planar form factor, and potential for low-cost manufacturing using semiconductor fabrication techniques are some of the main features that make metasurfaces ideal candidates for implementation of low-cost miniaturized optical systems. However, to become competitive for practical applications, metasurfaces should also offer specifications (e.g. efficiency, bandwidth, and wavefront error) comparable to their refractive counterparts. We have recently demonstrated diffraction-limited metasurface lenses with high efficiency using high refractive index nano-posts. Low numerical aperture (NA) metasurface lenses have more than 90% focusing efficiency, but the efficiency of the lenses with NA>0.5 decreases with increasing NA and drops to ~40% for NA=0.9, thus resulting in a trade-off between the NA and efficiency. Here we identify the main physical origin of this trade-off as the low transmission of large diameter nano-posts for transverse-magnetic (TM) polarized light incident at large angles, and show that the low transmission is caused by the excitation of undesired high order modes in these nano-posts. To overcome this issues, we present a novel approach for evaluating different metasurface designs in implementation of high NA metasurface components. The approach is based on adiabatic approximation of aperiodic metasurfaces by periodic gratings, and considers the effect of large deflection angles. Using the proposed design approach, we experimentally demonstrate more than 75% focusing efficiency for metasurface lenses with NA=0.7, and more than 70% deflection efficiency for 50-degree beam deflectors for unpolarized light at 915 nm.

10113-20, Session 5

Ultra-compact hyperspectrometer at visible wavelengths

Alexander Y. Zhu, Wei Ting Chen, Mohammadreza Khorasaninejad, Harvard Univ. (United States); Jaewon Oh, Univ. of Waterloo (Canada); Aun Zaidi, Ishan Mishra, Robert C. Devlin, Federico Capasso, Harvard Univ. (United States)

Optical spectroscopy is a well-established technique that has been used to obtain a rich variety of information of physical systems, ranging from chemical compositions to particle dynamics. Polarization measurements can reveal additional details of an object such as its texture and constituent material, as well as the nature of scattering or emission processes. Of particular interest is resolving the chirality: a typical example is the necessity of identifying optically isomeric (chiral) compounds in the synthesis of numerous pharmaceutical drugs, as well as disease diagnostics. Current tools capable of acquiring spectral or polarization information generally require the use of numerous optical components, such as focusing mirrors and multiple gratings mounted on a turret, or non-polarizing beamsplitters, waveplates and polarizers. They are therefore bulky and cost-ineffective. While compact spectrometers do indeed exist, the vast majority are limited to a single fixed spectral resolution and/or suffer from lack of polarimetric capabilities. In this context, recent advances in nanophotonics which have led to the development of meta-surfaces offer the ability to develop multifunctional devices comprising of a single ultra-thin surface. Using this concept, we demonstrate an ultra-compact hyper-spectrometer based on only titanium oxide metalenses and a CMOS camera. We achieve spectral resolutions as small as 0.3 nm and a total working wavelength range exceeding 130 nm in the visible range. It is also capable of extracting chiral information simultaneously. This two-component system is the ultimate compact configuration for a spectrometer and is promising for numerous spectro-polarimetry applications.

10113-21, Session 5

Robust design of microlenses arrays employing dielectric resonators metasurfaces

Fabrizio Silvestri, TNO (Netherlands) and Technische Univ. Eindhoven (Netherlands); Giampiero Gerini, TNO Defence, Security and Safety (Netherlands) and Technische Univ. Eindhoven (Netherlands); Stefan M. B. Bäumer, TNO (Netherlands)

In the last years much interest has grown around the concept of optical surfaces employing high contrast dielectric resonators of different sizes. By shaping their dimensions, the transmissive/reflective response of each resonator can be tuned to achieve almost perfect local control of phase and polarization of scattered fields [1,4]. However, a systematic approach for

the design of this optical surfaces under particular requirements has never been proposed. In this contribution we describe this approach applied to the robust design of an array of microlenses characterized by a numerical aperture of NA=0.19 with a field of view of FOV = ± 60 mrad in a bandwidth of 20 nm. Typically, dielectric resonators are engineered in such a way to have almost full transmissive surfaces with locally tunable phase. However, considering the multiple wavelengths and angles under which the lenses may work, it is difficult to get uniform transmission characteristics for all the dielectric resonators employed. The design strategy, here proposed, uses a particle swarm optimization routine to find the best resonator distribution able to meet the requirements considering both the amplitude and phase characteristics of the resonators surfaces. In the optimization process also the effects of possible manufacturing inaccuracies, such as variations of resonators' radii, are taken into account, allowing a robust design of the structure, within the given manufacturing tolerances. Different designs, operating at 405 nm and 635 nm, will be presented at the conference and their performances will be discussed under the point of view of their applicability in different application areas.

10113-22, Session 6

All-dielectric metasurfaces: enhanced nonlinearities and emission control *(Invited Paper)*

Igal Brener, Sandia National Labs. (United States)

Two-dimensional metamaterials (metasurfaces) have led to many exciting phenomena both in linear and nonlinear optics. The ability to tailor optical modes and radiation patterns combined with low losses make all-dielectric metasurfaces an interesting platform for nonlinear optics and interactions with emitters. The combination of dielectric metasurfaces made from nanostructured III-V semiconductors results in very high second and third optical nonlinearities. Additionally, using epitaxial and heterostructured III-V semiconductors as the constituent material for such metasurfaces enables the inclusion of high quality quantum emitters. We will present recent results on the interaction between high Q modes present in dielectric metasurfaces and epitaxial quantum dots.

10113-23, Session 6

Flat nonlinear optics: metasurfaces for efficient frequency mixing *(Invited Paper)*

Nishant Nookala, Jongwon Lee, Yingnan Liu, Mykhailo Tymchenko, Sebastian J. Gomez-Diaz, The Univ. of Texas at Austin (United States); Frederic Demmerle, Gerhard Boehm, Markus-Christian Amann, Technische Univ. München (Germany); Omri Wolf, Igal Brener, Sandia National Labs. (United States); Andrea Alù, Mikhail A. Belkin, The Univ. of Texas at Austin (United States)

The recent emergence of "flat" optical components has been spurred by the development of metasurfaces of subwavelength thickness that provide beam manipulation by controlling the phase of scattered fields at subwavelength scales. In order to extend this paradigm to the nonlinear optical case, metasurfaces with nonlinear response many orders of magnitude higher than that of traditional nonlinear crystals are required. Recently, we have reported metasurfaces with giant nonlinear response based on coupling plasmonic resonators to intersubband transitions within multi-quantum well semiconductor heterostructures for mid-infrared second-harmonic generation. We produced metasurfaces with record high nonlinear optical response of 1.2x10^6 pm/V and attain nearly 0.1% of mid-infrared second harmonic conversion efficiency in deeply subwavelength (lambda/20) films. We also demonstrated that is possible to attain continuous phase control of the nonlinear response at the individual nanoresonator level. I will review this work and present the results of our going efforts to overcome the conversion efficiency limitations in these metasurfaces, imposed by intensity saturation of intersubband transitions, and to extend the functionalities of these metasurfaces to nonlinear optical processed beyond second harmonic generation, such as frequency up- and down-conversion, parametric generation, and four-wave mixing.

This work was supported in part by AFOSR (FA9550-14-1-0105), ONR MURI (N00014-10-1-0942), Nano Initiative Munich (NIM), and the Friedrich Wilhelm Bessel Research Award from Alexander von Humboldt Foundation. Sample fabrication was carried out in the Microelectronics Research Center at the University of Texas at Austin, which is a member of the National Nanotechnology Coordinated Infrastructure.

10113-24, Session 6

Independent control of function and chromatic dispersion in diffractive optical devices with metasurfaces

Ehsan Arbabi, Amir Arbabi, Seyedeh Mahsa Kamali, Yu Horie, Andrei Faraon, California Institute of Technology (United States)

Diffractive optical devices have many applications in various fields of optics. A fundamental property of all diffractive devices is their negative chromatic dispersion: a diffractive grating always disperses light in the opposite order compared to a refractive prism made of a material with positive (normal) dispersion. Unlike refractive devices, chromatic dispersion in diffractive devices stems from geometrical features, and cannot be controlled via the intrinsic material dispersion. In addition to the always negative sign, the amplitude of diffractive chromatic dispersion is set only by the function of the device. For instance, the angular dispersion of a grating is always given by d?/d?=tan?(?)/? (where ? is the deflection angle and ? is wavelength), or the focal distance dispersion of a diffractive lens is given by df/d?=-f/?. Therefore, the chromatic dispersion of diffractive devices has always been set by their function (e.g. by the deflection angle for a grating or the focal distance for a lens), and could not be controlled separately. Here, we present our work on breaking this fundamental relation between the function and chromatic dispersion of diffractive devices using metasurfaces providing independent control over phase and group delays. We use a reflective dielectric metasurface to experimentally demonstrate gratings and lenses that have positive, zero, and extraordinary negative chromatic dispersion. Apart from its fundamental scientific value, this concept expands the applications of diffractive devices as it enables various types of chromatic dispersions. For instance, a special case would be a dispersionless lens operating over a wide bandwidth with the same focal distance.

10113-25, Session 6

Metasurfaces with controlled angular phase dispersion

Seyedeh Mahsa Kamali, Ehsan Arbabi, Amir Arbabi, Yu Horie, Andrei Faraon, California Institute of Technology (United States)

Metasurfaces are two-dimensional arrangements of nano-scatterers that enable control of phase, amplitude, and polarization of light with high efficiency and subwavelength resolution. They have enabled diffractive optical elements with enhanced functionalities and performance. Nevertheless, metasurface diffractive optical elements share many of the properties of regular diffractive optical elements. One of these properties is the response of diffractive elements to changing the angle of illumination: if the beam incident on a grating is rotated by an angle, all diffraction orders will rotate by corresponding angles in the same direction. More precisely, because of the constant grating momentum, the change in the sine of all diffraction angles will be equal to the change in the sine of the illumination angle.

Many optical devices of interest, however, do not require this type of behavior, which makes their implementation using metasurfaces very challenging. For instance retroreflectors, which reflect light incident from any angle to the same direction, or collimators, that deflect light coming from any angle to a single given direction, do not follow the regular diffractive optics angular response. We investigate properties of single-layer metasurfaces that enable devices like retroreflectors and collimators. We show that such metasurfaces should have the ability to control the phase, as well as the derivative of phase with respect to angle. We demonstrate designs that provide such control, and use them to show devices that defy the regular response of diffractive optical devices to changes in the illumination angle.

10113-26, Session 6

Nonlinear dielectric metasurfaces for frequency conversion and light modulation *(Invited Paper)*

Dragomir N. Neshev, The Australian National Univ. (Australia)

Dielectric metasurfaces have proven to be able to manipulate the wavefront of incoming waves with high transmission efficiency. The important next question is: Can they enable enhanced interaction with the light to transform its colour or to be able to control one light beam with another? Here we show how an ultra-thin surface of subwavelength thickens can enable enhanced light matter interaction for efficient frequency conversion and ultra-fast light modulation. In particular, we show how designer dielectric metasurfaces can enhance second and third harmonic generation resulting in complete nonlinear control of directionality and polarisation state of the harmonics. Furthermore, we demonstrate how such enhanced light matter interactions can lead to optical switching with unprecedented speed. Our results open novel applications in ultra-thin light sources, light switches and modulators, ultra-fast displays, and other nonlinear optical metadevices based on low loss subwavelength dielectric resonant nanoparticles.

10113-44, Session PWed

Three-dimensional metamaterial with auxetic behavior

Junhyun Kim, Dongheok Shin, Kyoungsik Kim, Yonsei Univ. (Korea, Republic of)

Poisson's ratio, which is defined as negative ratio of axial strain to the normal strain, is a material property used in elastic analysis. When we stretch an object, it is usually expected that object becomes thinner in cross section. Similarly, object is expected to thicker in cross section when compressed. In general, most materials have positive value of Poisson's ratio. However, several researches have been done on auxetic materials, namely, materials with negative Poisson's ratio. Researches have shown that auxetic material can lead to property enhancements, such as enhanced fracture toughness, energy absorption, shear resistance. Auxetic effect is exploited in various applications such as biomedicine, sports and smart transformation optics.

Here we, report the three-dimensional structure with rotating rigid regular prisms for auxetic behavior. We attempt to construct a structure by configuring regular prisms in regular configuration. First, we show that we can construct unit ce

10113-45, Session PWed

Meta-axicons for generating wavelength-independent sub-wavelength Bessel beams

Wei Ting Chen, Mohammadreza Khorasaninejad, Alexander Y. Zhu, Harvard Univ. (United States); Jaewon Oh, Harvard Univ. (United States) and Univ. of Waterloo (Canada); Robert Devlin, Aun Zaidi, Federico Capasso, Harvard Univ. (United States)

Bessel beams have attracted widespread attention due to their unique non-diffractive properties. Common approaches to generate Bessel beams involve the use of an axicon or an objective paired with an annular aperture. However, the former has a limited numerical aperture (NA) due to total internal reflection at the glass-air interface, while the use of an annular aperture blocks most of the incident light, resulting in low efficiency. Additionally, both approaches require an additional phase-modulating element to generate high-order Bessel beams adding further complexity and bulkiness to the system. Here, we use metasurfaces to demonstrate meta-axicons capable of generating Bessel beams of any order, with sub-wavelength feature size and additional functionalities that are not attainable with conventional components. Meta-axicons with high NA (up to 0.9) which are able to generate Bessel beams at wavelength 405 nm with full-width at half-maximum as small as ~ 150 nm were fabricated using a titanium oxide based atomic layer deposition process. This fabrication process ensures vertical sidewalls and low surface roughness. Moreover, by engineering the wavelength dependency of each phase elements, meta-axicon can generate Bessel beams with transverse intensity profiles independent of wavelength. Our high NA meta-axicons hold promise for advanced research and applications related to Bessel beams, such as laser fabrication, imaging, and optical manipulation.

10113-27, Session 7

Enhancement of nonlinear-optical effects in silicon nanodisks driven by magnetic Mie resonances *(Invited Paper)*

Andrey A. Fedyanin, Alexander S. Shorokhov, Maxim R. Shcherbakov, M.V. Lomonosov Moscow SU (Russian Federation); Dragomir N. Neshev, Yuri S. Kivshar, Nonlinear Physics Ctr., The Australian National Univ. (Australia)

The study of nonlinear effects with high-index dielectric nanoparticles is emerging as a promising alternative to plasmonic systems usually utilized for nonlinear nanophotonics, due to negligible Ohmic losses and low heating in combination with multipolar radiation characteristics of both electric and magnetic nature. In this contribution, we discussed novel nonlinear-optical effects, such as enhanced second- and third-harmonic generation in silicon nanodisks excited in the spectral range close to the magnetic dipole resonance of the individual disk. Each of the nanodisks exhibits both electric and magnetic Mie-type resonances that are shown to affect significantly their nonlinear response. We have observed the third-harmonic radiation intensity that is comparable to that of a bulk silicon slab and demonstrated a pronounced reshaping of the third-harmonic spectra due to interference of the nonlinearly generated waves augmented by an interplay between the electric and the magnetic dipolar resonances. We have also demonstrated all-optical switching of femtosecond laser pulses passing through subwavelength silicon nanodisks at their magnetic dipolar resonance. In z-scan experiments, we have observed a modulation of up to 60% and a spectral resonance shift of 6 nm when pumping the nanostructure at picojoule-per-disk powers. Third-harmonic generation from silicon nanodisks arranged in the form of quadrumers or trimer oligomers with varying distance between the nanoparticles is studied.

10113-28, Session 7

Resonant high-index metasurfaces: the magnetic response comes in to play *(Invited Paper)*

Ramon Paniagua Dominguez, Ye Feng Yu, Yuan Hsing Fu, Egor Khaidarov, Hanfang Hao, Boris Luk'yanchuk, Arseniy I. Kuznetsov, A*STAR - Data Storage Institute (Singapore)

Metasurfaces are planar arrangements of elements that are designed to present a particular response to an incident electromagnetic field. Due to their ability to control at will the phase, polarization and amplitude of the reflected and/or transmitted waves at a subwavelength scale they have gathered a great deal of attention among the research community.

Although the first metasurface proposals were realized with plasmonic particles, the focus is now turning into all-dielectric approaches, in order to mitigate losses and increase the device efficiencies. Besides the obvious advantage of loss reduction, when high-index, subwavelength particles are considered a whole new family of resonant, magnetic-like modes is accessible. This new set of modes, which cannot be excited in simple metallic particles, brings additional functionalities for these metasurfaces, as will be shown in this talk.

We will focus on the interesting effects that arise as a consequence of the far-field interference between electric and magnetic modes excited in the dielectric particles forming the metasurface and the strong modification of their scattering patterns as a consequence of this interference. In particular, we will show the possibility to realize so called ideal Huygens' secondary sources to generate a perfectly transmissive metasurface with full phase control. We will also show that these metasurfaces support a generalized version of Brewster's effect, in which the phenomenon is not restricted to a particular angle or polarization of incidence but can be tuned at will, and the different implications that this concept has.

10113-29, Session 7

Scattering and skin depth at the meso- and nanoscale

Nitish Chandra, The Univ. of North Carolina at Charlotte (United States)

Scattering from simple geometric shapes is often modeled in terms of a series expansion and field matching through satisfying boundary conditions at interfaces. From non-perfectly conducting objects, scattering can be considered in terms of the material's skin depth, d, and the object is assumed impenetrable if conducting regions are somewhat thicker than this. However, for finite sized scattering structures of the order of the wavelength, including layered structures, resonant scattering phenomena can occur and surface currents and surface charge densities can lead to surface waves and anomalous far-field scattering patterns that are dependent on properties much deeper than the skin depth. Resonant field components, both electric and magnetic can be responsible for this and the permeability of the object becomes important in providing a full description of the scattered field. Mie scattering from open cylinders, for example, is known to differ considerably from their semi-open or fully closed counterparts. We have modeled the scattering from objects capable of supporting a resonant phenomenon, i.e. non-Rayleigh scattering, in terms of the magnetic vector potential for cases when the skin depth varies as a function of conductivity. Observations made and explained at GHz frequencies are extended to tens and hundreds of THz and meso-scale and nanoscale structures. We propose that interpreting scattering data from objects of known size and geometry can be used to better characterize material properties at these high frequencies and associated phenomena such as kinetic inductance.

10113-31, Session 7

Quantum optomechanics experiments with photonic crystals *(Invited Paper)*

Simon Groeblacher, TU Delft (Netherlands)

Mechanical oscillators coupled to light via the radiation pressure force have attracted significant attention over the past years for allowing tests of quantum physics with massive objects and for their potential use in quantum information processing. Recently demonstrated quantum experiments include entanglement and squeezing of both the mechanical and the optical mode. So far these quantum experiments have almost exclusively operated in a regime where the light field oscillates at microwave frequencies. Here we would like to discuss recent experiments where we demonstrate non-classical mechanical states by coupling a mechanical oscillator to single optical photons. These results are a promising route towards using mechanical systems as quantum memories, for quantum communication purposes and as light-matter quantum interfaces.
In addition, we will also discuss efforts to perform these quantum optomechanics experiments at room temperature, in contrast to the currently purely cryogenic environments used. We investigate different materials systems, like SiN and SiC, in order to realize structures for these type of experiments.

10113-32, Session 8

Metasurfaces for advanced light management and thermal emission *(Invited Paper)*

Hamidreza Chalabi, Andrea Alù, The Univ. of Texas at Austin (United States)

In this talk, we will discuss our recent work in the area of wave manipulation with high-contrast metasurfaces, with special interest in manipulating optical wavefronts and thermal emission. In addition to our recent theoretical and experimental work in the area of gradient metasurfaces to manipulate the impinging light, we will discuss how similar concepts may be extended to thermal sources, to manipulate their emission features. Incandescent sources made of electrically-heated films suffer from low efficiencies and offer poor control over the directionality and spatial localization, as well as the spectral and polarization properties of the emitted light. We have recently demonstrated that, by nanostructuring a SiC surface, we can concentrate the thermal emission of a preselected spectral range into a well-defined location above the surface. Concentrating the thermal radiation can have direct impact on the design and operation of the future generation of thermo-photovoltaic cells in addition to providing the ability for local heat generation and moreover mitigate challenges associated with thermal management in low thermal budget devices. Our recent theoretical work suggests that gradient metasurface concepts may be suitably extended to tailor thermal emission control with a new degree of control.

10113-33, Session 8

Controlling nanoscale optical transmission with dielectric metasurfaces at visible wavelengths *(Invited Paper)*

Tapashree Roy, Haogang Cai, David Czaplewski, Argonne National Laboratory (United States); Daniel Lopez, Argonne National Lab. (United States)

A metasurface consisting of an array of dielectric resonators having overlapping electric and magnetic dipole resonances is known as Huygens' metasurfaces and is characterized by high transmission efficiency. Dielectric

Huygens' metasurfaces offer new possibilities to manipulate light without losses and are expected to be a key component for the development of novel flat optical devices and for the integration of optics with electronics and MEMS devices.

In this talk we describe dielectric metasurfaces consisting of TiO2 nanodisks that act as a Huygens' surface when illuminated with visible light. I'll demonstrate the possibilities this kind of metasurfaces offer to manipulate light, including diffraction-limited focusing, and the capabilities that can be achieved by integrating them onto MEMS devices.

10113-34, Session 8

High-finesse Fabry-Perot cavities with bidimensional Si3N4 photonic-crystal slabs *(Invited Paper)*

Samuel Deléglise, Ctr. National de la Recherche Scientifique (France); Xu Chen, Clement Chardin, Kevin Makles, Lab. Kastler Brossel (France); Charles Caër, IBM Research - Zürich (Switzerland); Sheon Chua, Lab. Kastler Brossel (France); Rémy Braive, Isabelle Robert-Philip, Lab. de Photonique et de Nanostructures (France); Tristan Briant, Lab. Kastler Brossel (France); Pierre-François Cohadon, Antoine Heidmann, Thibaut Jacqmin, Lab. Kastler Brossel (France) and Lab. de Photonique et de Nanostructures (France)

Two-dimensional photonic crystal slabs (PCS) offer an appealing alternative to distributed Bragg reflectors or filters for various applications. Indeed, their scattering properties, governed by Fano-resonances, have been used in areas as diverse as optical wavelength and polarization filters, reflectors, semiconductor lasers, photodetectors, bio-sensors, or non-linear optical components. Suspended PCSs also find natural applications in the field of optomechanics, where the mechanical modes of a suspended slab interact via radiation pressure with the optical field of a high finesse cavity. The reflectivity and transmission properties of a defect-free suspended PCS around normal incidence can be used to couple out-of-plane mechanical modes to an optical field by integrating it in a free space cavity. We have demonstrated the successful implementation of a PCS reflector on a high-tensile stress Si3N4 nanomembrane. We could measure the photonic crystal band diagram with a spectrally, angular, and polarization resolved setup. Moreover, a cavity with a finesse as high as 12 000 was formed using the suspended membrane as end-mirror of a Fabry-Perot cavity. These achievements allow us to operate in the resolved sideband regime where the optical storage time exceeds the mechanical period of low-order mechanical drum modes. This condition is a prerequisite to achieve quantum control of the mechanical resonator with light.

10113-35, Session 9

Silicon-based optical metasurfaces *(Invited Paper)*

Jason G. Valentine, Yuanmu Yang, Parikshit Moitra, Vanderbilt Univ. (United States); Ivan I. Kravchenko, Abdelaziz Boulesbaa, Alexander A. Puretzky, David B. Geohegan, Oak Ridge National Lab. (United States)

I will first discuss large-area metamaterials formed using self-assembly of an etch mask. The etch mask is based on polystyrene spheres assembled using a variant of nanosphere lithography. This etch mask is used to pattern a single layer of silicon resonators forming a reflector. The reflector, despite imperfections, has an average reflectivity greater than 99% over a 10 mm x 10mm area. More importantly, the reflectivity has a variance less than 0.25% over this area despite defects in the pattern. This tolerance to defects comes from the fact that the surface's response is dictated by the resonator shape rather than the periodicity of the array.

I will then discuss the development of silicon-based metasurfaces possessing sharp EIT-like resonances with a record high Q-factor of 483 in the near-infrared regime. The high-Q resonance is accomplished by employing Fano-resonant unit cells in which both radiative and non-radiative damping are minimized through coherent interaction among the resonators combined with the reduction of absorption loss. Combining the narrow resonance linewidth with strong near-field confinement, we demonstrate an optical refractive index sensor with a figure of merit (FOM) of 103. I will also discuss how the large local field enhancement can be used to realize a third harmonic conversion enhancement factor of 10^5 with respect to an unstructured silicon slab.

10113-36, Session 9

All-dielectric metamaterials for sub-diffraction light confinement *(Invited Paper)*

Saman Jahani, Zubin Jacob, Purdue Univ. (United States)

Here, we surpass the diffraction limit of light by a new class of all-dielectric artificial materials that are lossless. This overcomes one of the fundamental challenges of light confinement in metamaterials and plasmonics: metallic loss. Our approach relies on controlling the optical momentum of evanescent waves as opposed to conventional photonic devices which manipulate propagating waves. This leads to a counterintuitive confinement strategy for electromagnetic waves across the entire spectrum. We introduce two distinct photonic design principles that can ideally lead to sub-diffraction light confinement without metal. They are i) relaxed total internal reflection and ii) photonic skin-depth engineering. We present initial experimental results on a CMOS compatible platform that prove the enhanced confinement of our all-dielectric metamaterial design.

10113-37, Session 9

Aluminum plasmonic multicolor meta-hologram

Hui Jun Wu, Yao-Wei Huang, Wei Ting Chen, Wei-Yi Tsai, Pin Chieh Wu, National Taiwan Univ. (Taiwan); Chih-Ming Wang, National Dong Hwa Univ. (Taiwan); Greg Sun, Univ. of Massachusetts Boston (United States); Din Ping Tsai, National Taiwan Univ. (Taiwan)

Metamaterials, with the ability of tailoring optical properties of materials, have been applied to holograms recently, which has shown the priorities of switchable polarization and multicolor image comparing with the conventional holograms. However, the current metasurface based multicolor holograms have suffered the problems of narrow band and low efficiency in phase modulation for gold and silver when their feature dimensions are in few tens of nanometers. Interestingly, aluminum with higher plasma frequency could yield surface plasmon resonance across a broader range of the spectrum ranging from visible to UV. Metasurfaces incorporating with the aluminum offer the unique opportunity to extend the working wavelength to cover the entire visible spectrum for the generation of full color meta-holograms.

Here we demonstrated a phase modulated multicolor meta-hologram that is polarization dependent and capable of producing images in red, green and blue colors. The metahologram is made of aluminum nanorods that are arranged in a two-dimensional array of pixels with surface plasmon resonance in the visible to UV range. The aluminum nanorod array is patterned on a 30 nm thick SIO2 spacer layer sputtered on top of a 130nm thick aluminum mirror. With proper design of the structure, we obtain resonances of narrow bandwidths to allow for implementation of multicolor scheme. Taking into account of the wavelength dependence of the diffraction angle, we can project images to specific locations with

predetermined size and order. With tuning of aluminum nanorod size, we demonstrate that the image color can be continuously varied across the visible spectrum.

10113-38, Session 9

Tailoring Bloch modes in Tamm plasmons structures

Lydie Ferrier, Cécile Jamois, Institut des Nanotechnologies de Lyon, Univ. de Lyon (France); Clémentine Symonds, Joël Bellessa, Institut Lumière Matière, Univ. de Lyon (France); Taha Benyattou, Institut des Nanotechnologies de Lyon, Univ. de Lyon (France)

Tamm plasmons are electromagnetic states located at the interface between a dielectric Bragg mirror and a metal [1]. Contrary to conventional surface plasmons, Tamm plasmons can exist in both TE and TM polarization and its parabolic dispersion lies above the light cone which allow a direct optical excitation at normal incidence. Besides, the Tamm mode confinement can be obtained by simply patterning the thin metallic film, such as microdisks [2,3] or microrectangles [4]. Here, we aim at obtaining ultimate confinement using photonic crystal periodic structures in the metallic layer.

The samples are constituted by a DBR with 4 pairs of l/4n layers of Si and SiO2 above which periodic metallic patterns are defined using e-beam lithography and a 50nm gold deposition. Lift-off is performed at the end of the process. The period of the gratings is chosen to obtain a Tamm Bloch mode around 1.3micrometer.

Microreflectivity experiments show that Tamm Bloch modes exist in such 1D periodic structures. Using an original design, we create a 1D photonic band gap as large as 140nm. Finally, we will present experimental results on cavity-confined Tamm Bloch modes. All results are in good agreement with numerical calculations.

[1] M. Kaliteevski et al., Phys. Rev. B 76, 165415 (2007)

[2] O. Gazzano et al., Phys. Rev. Lett. 107, 247402 (2011)

[3] C. Symonds et al., Nanoletters, 13 (7), pp 3179–3184 (2013)

[4] G. Lheureux et al., ACS Photonics 2 (7), pp 842–848 (2015)

10113-39, Session 9

Optical metasurface based on hybrid high-contrast dielectric gratings for visible and near-IR ranges

Yuhan Yao, Yifei Wang, Yuanrui Li, He Liu, Boxiang Song, Wei Wu, The Univ. of Southern California (United States)

In the past decade, subwavelength high contrast gratings (HCGs) have been developed and studied, which has led to many applications. The broadband reflectance in HCGs mainly comes from the contrast between the grating material and its surrounding environment, so high-index and low-loss materials are required for making HCGs. Compared with infrared (IR) ranges, building HCGs in visible or near-IR wavelength ranges is much harder due to the limitation of optical materials.

In order to overcome the challenge of materials in making HCGs in visible to near-IR ranges, hybrid HCGs are proposed. The design of hybrid HCGs is a combination of low-loss and low-index materials and high-loss and high-index materials. In order to reduce the optical loss due to the incorporation of high-loss material, optical modes must be manipulated to be confined in the low-loss region.

In our work, the structure and parameters for hybrid HCGs are optimized based on numerical study (both FDTD and RCWA). As a proof-of-principle demonstration, hybrid HCGs composed of amorphous silicon, silicon nitride and silicon dioxide are optimized. The optimal structure has a broadband reflectance (>90%) in visible to near-IR ranges. The design demonstrates a great fabrication tolerance to line width, dielectric thicknesses and sidewall verticality. The hybrid HCGs are patterned by nanoimprint lithography. Reactive ion etching at cryogenic temperature is optimized for the best etching profile. More details on design, fabrication and measurement will be presented at the conference.

10113-40, Session 10

Approach towards actively tunable mid- to far-Infrared nanophotonics *(Invited Paper)*

Joshua D. Caldwell, Adam D. Dunkelberger, Chase T. Ellis, Virginia Wheeler, Michael A. Mastro, Marc Currie, Joseph G. Tischler, Jeffrey C. Owrutsky, Igor Vurgaftman, Chul Soo Kim, Mijin Kim, Mario G. Ancona, U.S. Naval Research Lab. (United States)

The spectral range encompassing the mid- (3-8 um) and long-wave (8-15 um) infrared provides a wealth of information, for instance, regarding the local temperature variation and molecular vibrations. In addition, two ‘atmospheric windows’ (~3-5 and 8-12 um) occur within these bands that open up the potential for optical communications, obscurant-free imaging, extended range signaling, and stand-off chemical sensing. However, optical components in this spectral range are less than optimal with hygroscopic and/or brittle material characteristics, are rarely compact, and have a small ratio of the photon to thermal energies. Polaritonic materials may allow these challenges to be overcome with optical components that are sub-diffractional in scale and composed of more traditional materials, and can thereby lead to new kinds of optical sources, components and detectors in these longer wavelengths of interest. Furthermore, this approach can exploit surface plasmon polaritons, typically supported by highly doped semiconductors, or surface phonon polaritions, incorporating polar dielectric and semiconductor crystals. Here we discuss general concepts and our recent data demonstrating active tuning of local polaritonic resonators, including free-carrier injection, nanoscale thickness phase-change films and ferroelectric layers. Initial results detailing potential near term applications will also be discussed, in particular demonstrating an approach towards realizing modulated IR sources based on thermal emitters.

10113-41, Session 10

Optimization of high-contrast metastructure silicon waveguides for wavelength-tunable delay *(Invited Paper)*

Karen Grutter, U.S. Army Research Lab. (United States); Stephen Anderson, Rensselaer Polytechnic Institute (United States) and U.S. Army Research Lab. (United States); Weimin Zhou, U.S. Army Research Lab. (United States)

The ability to tune the delay of an optical signal is an important function in a variety of photonic applications, including signal buffering, optical coherence tomography, and phased-array antennas. Recent modeling work has shown that high-contrast metastructure waveguides can be designed for a wide range of delay tuned by carrier injection or signal wavelength. When these tunable delay waveguides are integrated with an array of photodectors and RF transmitters, two-dimensional, wide-angle RF beam steering can be achieved using these two parameters.

In this work, we further explore the parameter space of these waveguides to maximize the delay change over optical wavelength while maintaining low insertion loss. With high-contrast grating metastructures attached in-plane to a silicon ridge waveguide, finite-difference-time-domain simulations indicate delay ranges greater than 50 ps are possible over a waveguide length of less than 1 mm, a significant improvement over previous designs. By cascading a series of these delay lines as in the previously-described architecture, we can achieve an RF beam steering angle of more than 90°

along one axis. Importantly, the critical dimensions of these structures are large enough that they can be fabricated using standard optical lithography processes, making this design more scalable than comparable photonic crystal structures. Data from fabricated waveguides will be presented at the conference.

10113-42, Session 10

Liquid-crystal tunable metasurfaces for phase modulation and beam deflection

Andrei Komar, Zheng Fang, The Australian National Univ. (Australia); Isabelle Staude, Friedrich-Schiller-Univ. Jena (Germany); Manuel Decker, Andrey E. Miroshnichenko, The Australian National Univ. (Australia); Justus Bohn, Friedrich-Schiller-Univ. Jena (Germany); Ramon Paniagua Dominguez, Ye Feng Yu, Arseniy I. Kuznetsov, A*STAR - Data Storage Institute (Singapore); Yuri S. Kivshar, Dragomir N. Neshev, The Australian National Univ. (Australia)

All-dielectric optical metasurfaces represent a new platform that is able to change electromagnetic field dramatically, while having thickness much smaller than the optical wavelength. The properties of metasurface depends critically on the geometry of its nanostructuring, therefore they are pre-set during the fabrication process. However, a number of practical application of such metasurfaces requires the dynamic change of their properties with operation. Embedding the metasurface in LC we can offer unique opportunities for such tuning and control of their properties. Here we show that by applying voltage across the LC or by varying its temperature we are able to control the spectral position of the metasurface's electric and magnetic resonances. Using this method, we demonstrate experimentally the tuning of the properties of homogeneous metasurface consisted from array of equal elements as well as switch on and off different metasurface devices that use nanostructures with gradient geometries.

In particular, we show that applying voltage across the LC cell (one substrate of which is a Si disk metasurface), we can change the spectral position of electric and magnetic resonances thus changing intensity and phase of transmitted electromagnetic wave. To demonstrate possibility of thermal controlling of metasurface with special geometry, we further utilize gradient metasurface that deflect light beams. By heating the LC to the critical temperature we can switch the transmitted beam from straight propagation to angular deflection. Overall, by combining developed LC technologies with the emerging field of nanostructured metasurfaces we show the potential for novel ultra-thin tunable optical devices.

10113-43, Session 10

Tunable light-matter interaction with quantum spillover and electrostatic gating in 2D materials *(Invited Paper)*

Nicholas X. Fang, Massachusetts Institute of Technology (United States)

Recently, exciting new physics of plasmonics has inspired a series of key explorations to manipulate, store and control the flow of information and energy at unprecedented dimensions. In this talk I will report our recent efforts on controlling light absorption and emission process through quantum effects in sub-20nm scale coatings. For example, we experimentally demonstrated strong absorption in the visible spectrum by thin oxides less than 20nm of thickness assisted by silver films. We found such a broadband light absorption below the bandgap of the oxide is a manifestation of quantum electron tunneling that penetrate into the thin oxide layer, and it is controlled by the static dielectric constant of the oxide instead of dopant. We also found quantum emitters on a graphene-hBN heterostructure can be switched on and off at mid infrared, by transferring energy into surface phonon polaritons, and this effect can be electrically tuned by biasing the graphene layer. I will also discuss application of these nanostructure for efficient light harvesting and controllable emission, with potential impact in high resolution mid-IR spectroscopy and imaging.

Conference 10114: Quantum Dots and Nanostructures: Growth, Characterization, and Modeling XIV

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10114-1, Session 1

High-diffraction-efficiency quantum-dots-doped liquid-crystals for holographic 3D display *(Invited Paper)*

Hongyue Gao, Jicheng liu, Zhiqiang Zheng, Qiuxiang Yao, Pan Liu, Shanghai Univ. (China)

Holographic 3D display is a true 3D display technology, which can provide realistic 3D images without any special eyewear for observers. It may be ultimately developed into holographic 3D televisions and holographic 3D projectors. Static holographic 3D display or holograms stored in materials has shown a perfect 3D display of holography. However, dynamic holography has not been applied in 3D video display because of limitations of current holographic display devices-spatial light modulators and slow-response dynamic holographic materials with hologram refresh rate, less than 25 Hz. We achieved real-time dynamic holographic 3D display in Quantum Dots doped liquid crystal films Holographic 3D video display with refresh rate, more than 25 Hz, was realized using them. Moreover, they are easier to fabricate large-size color video-rate holographic 3D display screens by using these materials. We have designed holographic 3D video display systems and built a holographic 3D TV and holographic 3D projector using these Quantum Dots doped liquid crystal films as screens. This paper will focus on property and holographic 3D video display of the Quantum Dots doped liquid crystals, and present their potential applications in large-size, high-definition, and color holographic true 3D video displays.

10114-2, Session 1

Nanowire separate absorption-multiplication avalanche photodetectors operating at 1064 nm *(Invited Paper)*

Alan Farrell, Baolai L. Liang, Univ. of California, Los Angeles (United States); Xiao Meng, Diana L. Huffaker, Cardiff Univ. (United Kingdom)

Avalanche photodetectors (APDs) operating at 1064 nm are an integral component of light detection and ranging (LiDAR) systems used in imaging technologies such as acquisition tracking and pointing (ATP) and airborne topographic mapping. Current state-of-the-art APDs utilize a separate absorption-multiplication (SAM) structure using an $In_{0.53}Ga_{0.47}As$ absorber lattice-matched to an InP multiplication layer. When operated in Geiger mode, these detectors are limited by the dark count rate caused by generation current in the InGaAs, making low-temperature operation necessary. At low temperature, trap-assisted tunneling (TAT) in the InP limits the performance. Although in theory it is possible to reduce generation current in the InGaAs by reducing the indium fraction (while still effectively absorbing at 1064 nm), in practice the reduction of bulk generation current is offset by the poor material quality resulting from lattice mis-matched growth on InP. In this work, we investigate the nanowire platform as a means to overcome this limitation. By taking advantage of the ability to grow high quality lattice mis-matched materials using selective-area epitaxy, two key design improvements are implemented: 1) the indium composition of the absorber is reduced to 30%, and 2) the InP multiplication region is replaced by AlGaAs. The reduced indium content in the InGaAs absorber reduces generation current by two orders of magnitude, while the large bandgap of AlGaAs reduces TAT by three orders of magnitude. This results in an improvement in Geiger mode operation over all temperature ranges. Geiger mode characterization will be presented in detail, including dark count rate, photon detection efficiency, and jitter.

10114-3, Session 1

Physics and technology of nanowire photodetectors *(Invited Paper)*

Håkan Pettersson, Halmstad Univ. (Sweden) and Lund Univ. (Sweden)

Over the last two decades there has been a dramatic increase in research activities related to semiconductor nanowires (NWs) due to their exciting prospects for implementation of novel high-performance electronics and photonics compatible with main-stream silicon technology. In this talk, I will give an overview of our research efforts on infrared photodetectors based on InP/InAsP semiconductor NWs. I will discuss growth, processing and characterization of both single NW devices and large square millimeter array devices comprising millions of NWs connected in parallel. The electrical data generally display excellent rectifying behavior with small leakage currents. From optical measurements, combined with modeling, we conclude that the photocurrent generation depends strongly on the geometry and doping of the NW devices. Properly designed, the absorption of IR radiation in array devices can be significantly enhanced by nanophotonic resonances induced by the geometry and spatially matched to the position of the embedded p-n junctions in the NWs yielding high-efficiency photovoltaics. We have also carried out in-depth studies of InP NW arrays with multiple enclosed axial InAsP quantum wells for broadband and thermal imaging applications. Finally, I will discuss our recent research efforts targeting single InP/InAsP NW avalanche photodetectors with separate absorption and multiplication regions. The presented photodetectors can potentially be grown on cheap silicon substrates due to the small footprint of the NWs. Successfully developed, novel low-cost and high-performance detector families for optical communication, thermal imaging and solar cell applications can be realized.

10114-4, Session 2

Lasing in a single nanowire with quantum dots *(Invited Paper)*

Jun Tatebayashi, Yasuhiko Arakawa, The Univ. of Tokyo (Japan)

Nanowire (NW) lasers have recently attracted increasing attention as ultra-small, highly-efficient coherent light emitters in the fields of nanophotonics, nano-optics and nanobiotechnology. Although there have been several demonstrations of single NW lasers utilizing bulk materials, it is crucial to incorporate lower-dimensional quantum nanostructures into the NW in order to achieve superior device performance with respect to threshold current, differential gain, modulation bandwidth and temperature sensitivity. The quantum dot (QD) is a useful and essential nanostructure that can meet these requirements. In this presentation, we will talk about our recent research activity regarding room temperature lasing of a single GaAs NW containing 50-stacked InGaAs/GaAs QDs. The NW cavities consist of multiple InGaAs/GaAs heterostructures acting as a QD active material, which are grown on shallow (<45 nm) GaAs core NWs and followed by GaAs/AlGaAs/GaAs core/shell/cap structures. Lasing oscillation is achieved at the emission wavelength of 900 nm by properly designing the NW cavity and tailoring the emission energy of each QD to enhance the optical gain. Obtained threshold pump pulse fluence is 179 uJ/cm2 at room temperature

and the characteristics temperature is 133K which is higher than that of conventional bulk NW lasers. Our demonstration paves the way toward ultra-small lasers with extremely low-power consumption for integrated photonic systems. Furthermore, we will discuss our recent results on the demonstration of two different types of NWQD lasers with distributed Bragg reflectors in order to improve the device performance of the NWQD lasers.

10114-5, Session 2

Bottom-up nanobeam laser on silicon-on-insulator

Hyunseok Kim, Univ. of California, Los Angeles (United States); Wook-Jae Lee, Cardiff Univ. (United Kingdom); Alan Farrell, Pradeep N. Senanayake, Univ. of California, Los Angeles (United States); Diana L. Huffaker, Univ. of California, Los Angeles (United States) and California Nano-Systems Institute (United States) and Cardiff Univ. (United Kingdom)

The integration of III-V compound semiconductor-based coherent light sources on silicon and silicon-on-insulator (SOI) substrates has been investigated extensively in the field of Si photonics and optoelectronics. Although monolithic integration of III-V on Si has advantages compared with wafer bonding techniques in terms of CMOS compatibility, large-volume productivity and cost efficiency, this bottom-up approach has been limited due to the fabrication difficulties stemming from the differences in lattices constants and thermal expansion coefficients between III-V and Si.

Here, we report bottom-up integrated nanobeam lasers composed of one-dimensional (1-D) III-V nanowire arrays on SOI substrates. Nanowires act as both a gain medium and a nanobeam cavity, where the pitch and dimension of the nanowires are carefully designed to have high quality factor of ~80,000 and small device size of ~6?0.2 um. A catalyst-free selective-area epitaxy method is employed to lithographically control the position of nanowires. This approach not only enables the growth of high-quality III-V materials on Si by confining the interface area to nanoscale, but also prevents the formation of deep-level traps from foreign metallic catalysts. InGaAs/InGaP core/shell nanowires are integrated on SOI by metal-organic chemical vapor deposition. As the lattice-matched InGaP shell effectively minimizes surface recombination and enhances radiative emission efficiency, the fabricated nanobeam laser operates by optical pumping at room temperature at the lasing wavelength of ~1100 nm with the threshold pump fluence of ~15 uJ/cm2. This accomplishment will be an important step toward next-generation light sources on Si for photonic and optoelectronic applications.

10114-6, Session 2

InGaAs/InP quantum-well-on-nanopillar LED on a silicon substrate using position-controlled MOCVD *(Invited Paper)*

Saniya Deshpande, Indrasen Bhattacharya, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

We demonstrate catalyst-free metal organic chemical vapor deposition (MOCVD) growth of position-controlled InP nanopillars on Si substrates for the first time. The nanopillars were grown at a low growth temperature of 460°C, compatible with CMOS back-end integration. Resulting arrays of nanopillars show high yield of ~97% and uniformity ~10% across pitch variation from 0.5-50 ?m. Nanopillars grow vertically, in single-phase, wurtzite crystalline form. Defects terminate close to the InP/Si interface and the nanopillars grow without any extended defects. The taper angle and hence emission characteristics of the nanopillars can be engineered by tuning growth parameters. Site-controlled nanopillars show wurtzite emission at 1.42 eV with a narrow linewidth (~50 meV). Time resolved photoluminescence reveals long lifetimes ~4 ns at room temperature, which points to a low, bulk-like surface recombination velocity and excellent optical properties, despite the nanopillar geometry. Core-shell p-n junction devices were grown on n-Si substrate by introducing dopants. Five InGaAs/InP quantum wells were incorporated in the active region of the diode heterostructure to obtain efficient silicon transparent electroluminescence from the nanopillar LED. Quantum well emission can be tuned over 1450-1520 nm with pitch variation in nanopillar arrays. The total estimated light output from a single nanopillars LED is 1.6 ?W at room temperature. This device is a first step towards the large-scale integration of highly efficient light sources on silicon.

10114-7, Session 2

Optical spectroscopy of P-GaAs nanopillars on Si for monolithically-integrated light sources

Juan Salvador Dominguez Morales, Shumithira Gandan, Ctr. for Advanced Photonics and Process Analysis, Cork Institute of Technology (Ireland) and Tyndall National Institute, Univ. College Cork (Ireland); Dingkun Ren, Univ. of California, Los Angeles (United States); Diana L. Huffaker, Univ. of California, Los Angeles (United States) and California NanoSystems Institute, Univ. of California at Los Angeles (United States) and Cardiff Univ. (United Kingdom); Tomasz J. Ochalski, Ctr. for Advanced Photonics and Process Analysis, Cork Institute of Technology (Ireland) and Tyndall National Institute, Univ. College Cork (Ireland)

In this work, we study the optical properties and emission dynamics of the novel nanostructure p-GaAs nanopillars (NPs) on Si. The integration of III-V optoelectronics on Si substrates is essential for next generation high speed communications. NPs on Si are good candidates as gain media in monolithically integrated small-scale lasers on silicon. In order to develop this technology an in depth knowledge of the NP structure is necessary to resolve its optimal optical properties.

The optical characterization which has been carried out consists of the emission analysis for different NPs geometries. We measured NPs with different combinations of pitch (of the order of a few ?m) and diameter (of the order of tens of nm). A comparison of intensities for the various NPs provides us with the most efficient geometry. The quality of the crystal grown has been studied from temperature-dependent and power-dependent photoluminescence (PL). A red shift and a significant reduction of the intensity are observed with an increase in temperature and decrease in excitation powers. The activation energy also suggests an important presence of non-radiative recombination in the NPs. Finally, we observed a reduction in decay times with rising temperatures. The long order of decay (a few ns) is due to the p-dopant in GaAs. These results will contribute to the further optimization of p-GaAs NPs structures

10114-8, Session 3

Shape and confinement control in mid and far infrared nanocrystals

Clement Livache, Bertille Martinez, Institut des NanoSciences de Paris, Univ. Pierre et Marie Curie (France) and Ctr. National de la Recherche Scientifique (France); Eva Izquierdo, Marion Dufour, ESPCI (France); Herve Cruguel, Sebastien Royer, cnrs (France); Xian Zhen Xu, ESPCI (France); Sandrine Ithurria, Ecole Supérieure de Physique et de Chimie Industrielles de la Ville de Paris

(France); Emmanuel Lhuillier, Institut des NanoSciences de Paris, Univ. Pierre et Marie Curie (France) and Ctr. National de la Recherche Scientifique (France)

While Colloidal Quantum dots (CQD) are now integrated as phosphor for display, even more interest is brought on their use for optoelectronic. This is especially true in the infrared where current technologies remain expensive. In this paper we discuss about self-doped CQD of mercury chalcogenides. We have developed a new synthesis for HgSe CQD with tunable optical features from 3 to 20 μm and with surface chemistry which lead to very high carrier mobility up to 100cm2.V-1s-1. This material raises great promises for the design of low cost infrared photodetector however more need to be understood about the origin and tunability of their self-doping. This is critical because the doping value will drive the absorption and dark photocurrent magnitude. We elucidate the origin on the doping and demonstrate that it is bulk process. Moreover we evidence that a control of the doping in the 0.1 to 1 electron per nanocrystal is achievable thanks to surface ligand exchange. We additionally propose a model to quantify the surface dipole of the used ligands from optical measurements. The transport properties of the nanocrystal are finally tested in an electrolyte gated transistor configuration.

10114-10, Session 3

Synthesis of CdSe quantum dot and its surface functionalization for photovoltaic application

Sidney A. Lourenço, Gabriel D. Rocha, Marco A. T. Silva, Univ. Tecnológica Federal do Paraná (Brazil); Felipe B. Soares, Univ. Estadual de Londrina (Brazil)

This work presents a colloidal synthesis of CdSe semiconductor Quantum dots and its surface modification by ligand exchange reaction with thiol and MPA molecules for photovoltaic and QD-OLED applications. X-ray diffraction (XRD), optical absorption (OA) and photoluminescence (PL) techniques were used to confirm QD growth and its surface modification. Colloidal semiconductor nanocrystals, also known as quantum dots (QDs), have attracted great attention since they have interesting size-dependent properties due to the quantum confinement effect. These nanoparticles are highly luminescent and have some potential applications in different technological area, including biological labeling, light-emitting diodes and photovoltaic devices. The CdSe QDs are synthesized from cadmium oxide and elemental selenium using a kinetic growth method, where particle size depends on reaction time and temperature. Briefly, the chemical synthesis process starts with two precursor solutions that are then mixed together to start the nucleation and growth of the QDs. The first precursor is the (Se-TOP) solution prepared by combining Se and 1-octadecene (ODE) in a 10 mL round-bottom flash clamped over stirrer hot plate. A syringe is used to injected trioctylphosphine (TOP) to the same flask. The second solution is CdO dissolved with oleic acid (OLEA) in ODE solvent. Then some of the Se-TOP solution is injected into the Cd precursor when the temperature reaches 225 ºC. Because of the dependence of the size of nanoparticles with time, samples of approximately 1 mL were removed at frequent time intervals. Then the samples were washed and disperse on toluene. After obtained the QD samples with different size, modification on surface was made by the process of ligand exchange reaction. After QD synthesis and surface modification processes, XRD, OA and PL were obtained to study QDs growth and its surface modification .

10114-11, Session 3

Influence of particle-size distribution and shell imperfections on the dielectric permittivity and optical response of PS/Au and PS/Ag nanoshells: modelling, synthesis, and optical characterization

Daniel Nascimento Duplat, Technische Univ. Delft (Netherlands); Daniel Mann, DWI an der RWTH Aachen e.V. (Germany); Pascal Buskens, DWI an der RWTH Aachen e.V. (Germany) and TNO (Netherlands); Man Xu, TNO (Netherlands) and Technische Univ. Delft (Netherlands); Aurèle J. L. Adam, H. Paul Urbach, Technische Univ. Delft (Netherlands)

Metallic nanoshells are spheroidal nanoparticles consisting of a dielectric core nanosphere surrounded by a metallic thin layer. Differences in the core-to-shell size ratio lead to different optical responses, which imposes not only to the fabrication process an important role, but also to the knowledge about the dielectric permittivity of the materials involved in the synthesis. We report a detailed seed-to-growth novel method of fabrication of high aspect ratio Polystyrene/Silver-or-Gold nanoshells with precise size control of the shell thickness. Analyses about the optical effects on variation of shell thickness, core diameter, aggregation of the nanoparticles and possible effects of oxidation are also reported with the use of imaging methods, like FESEM, HR-TEM, and STEMEDX.

A full analysis of the optical response of those nanoparticles is made by the comparison between experimental results, obtained by light extinction spectrophotometry, and numerical calculations using Extended Mie Theory applied to multi-layered nanoshells and Finite Element Method (FEM). Changes in the relative dielectric permittivity of the metals due to the fabrication process are extensively discussed, and the effects of Gaussian-like size distributions are also taken into account. With a fitted dielectric permittivity characterizing the metal in the nanoshell particles, our numerical modelling of the optical response of the nanoshell presents a precise matching with the measured extinction.

10114-12, Session 3

Anisotropic-polarised emission of single colloidal nanoplatelets

Fu Feng, Thu Loan N'Guyen, Michel Nasilowski, Univ. Pierre et Marie Curie (France); Clotilde M. Lethiec, The Univ. of Chicago (United States); Benoit Dubertret, Ecole Supérieure de Physique et de Chimie Industrielles de la Ville de Paris (France); Laurent Coolen, Agnès Maître, Univ. Pierre et Marie Curie (France)

Efficient coupling of nanoemitters to photonic or plasmonic structures requires the control of the orientation of the emitting dipoles. Nevertheless controlling the dipole orientation remains an experimental challenge. Many experiments rely on the realization of numerous samples, in order to be able to statistically get a well aligned dipole to realize an efficient coupling to a nanostructure. In order to avoid these statistical trials, the knowledge of the nature of the emitter and its orientation is crucial for a deterministical approach. We developed a method [1],[2] relying on the combination of polarimetric measurement and emission diagram which gives fine information both on the emitting dipolar transition involved and on the dipolar orientation

We analyse by this method square and rectangle single colloidal CdSe/CdS nanoplatetelets. We demonstrate that their emission can be described by just by two orthogonal dipoles lying in the plane of the platelets. More surprisingly the emission of the square nanoplatelets is not polarised whereas the rectangle one is. We demonstrate that this polarized emission is

due to the rectangular shape anisotropy by a dielectric effect.

[1] C. Lethiec, et al, Three-dimensional orientation measurement of a single fluorescent nanoemitter by polarization analysis, Phys. Rev. X 4, 021037 (2014),

[2] C. Lethiec et al, Polarimetry-based analysis of dipolar transitions of single colloidal CdSe/CdS dot-inrods, New Journal of Physics 16, 093014 (2014)

[3] S. Ithurria et al, colloidal nanoplatelets with 2 dimensional electronic structure, Nature Materials 10, 936 (2011)

10114-13, Session 4

Electrically Injected AlGaN nanowire deep ultraviolet lasers on Si *(Invited Paper)*

Songrui Zhao, Xianhe Liu, McGill Univ. (Canada); Zetian Mi, Univ. of Michigan (United States) and McGill Univ. (Canada)

Low threshold, high efficiency deep ultraviolet (UV) lasers are important for a broad range of applications, including biochemical sensing, medical diagnostics, and disinfection. To date, however, it has remained challenging to achieve electrically injected AlGaN quantum well lasers in the deep UV spectral range. We have performed a detailed investigation of the molecular beam epitaxial (MBE) growth and characterization Al-rich AlGaN nanowire heterostructures on Si substrate. We have demonstrated electrically injected AlGaN nanowire lasers operating in the UV-B and UV-C bands, which can exhibit a very small threshold current density (~ 300 A/cm2) at room temperature.

AlGaN nanowire heterostructures were grown directly on Si substrate by plasma-assisted MBE under nitrogen rich conditions, which are vertically aligned on the Si substrate along the c-axis. The AlGaN nanowire laser heterostructures consist of GaN:Si (250 nm), AlGaN:Si (100 nm), AlGaN (100 nm), AlGaN:Mg (100 nm), and GaN:Mg (10 nm) layers. Such vertically aligned, randomly distributed AlGaN nanowires can lead to strong photon confinement, due to Anderson localization of light. Moreover, under nitrogen-rich growth conditions, strong atomic-scale compositional modulations were observed in AlGaN nanowires, which can lead to three-dimensional quantum confinement of charge carriers and therefore significantly reduce the transparency carrier density. The fabrication of electrically injected AlGaN nanowire lasers involved the use of standard photolithography and contact metallization techniques. Electrically injected lasers operating at 262 nm and 289 nm have been demonstrated, with the threshold current density ~ 300 A/cm2, which is orders of magnitude lower compared to conventional AlGaN quantum well lasers.

10114-14, Session 4

MBE growth of ordered InGaN/GaN nano/microrods: from classical/quantum light sources to nanotransistors and pseudosubstrates *(Invited Paper)*

Enrique Calleja, Univ. Politécnica de Madrid (Spain)

Selective Area Growth (SAG) by Molecular Beam Epitaxy (MBE) is one of the best approaches to develop a variety of nanostructures on different substrates. Ordered axial InGaN/GaN nanoLED structures were grown on GaN/sapphire templates as well as on GaN buffered Si(111) substrates. Core-shell InGaN/GaN microstructures can also be grown following two approaches: i) from top–down (etched) GaN cores and ii) from bottom-up GaN cores. In both cases a subsequent conformal growth of InGaN layers was achieved. Based on this approach, core-shell nanoLED arrays were successfully fabricated.

A basic aspect of SAG refers to the initial stages of nanocrystals nucleation within the nanoholes that lead to their stable hexagonal structure and the efficient filtering of dislocations coming from the substrate, strongly dependent on the nano/microrod geometry.

A common observed feature is that In incorporation depends strongly on the crystal plane considered, either m- or r-plane, giving rise to two InGaN related emissions. Exploiting this effect, dot-in-a-wire InGaN structures were grown embedded in ordered GaN nanorods acting as Single Photon Emitters.

Nano/microrods can also be used as nanoFET transistors with a semi-cylindrical gate direct contact allowing for a very tight electrostatic control of the channel.

SAG is also used to grow ordered nanostructures on semi-polar and non-polar orientations GaN/sapphire templates with the aim to fabricate ternary pseudo-substrates with tailored lattice constant and very high crystal quality.

10114-15, Session 4

Advances in selective epitaxy for GaN nanowire devices *(Invited Paper)*

Kris Bertness, National Institute of Standards and Technology (United States)

Application of selective epitaxy methods to the growth of GaN nanowires provides a degree of morphology control that enables a variety of novel device applications. This talk will describe one method of selective epitaxy of GaN on Si substrates making use of GaN/AlGaN buffer layers and SiNx mask layers. The nanowires are grown with molecular beam epitaxy at high growth temperatures where N-polar nanowires will selectively nucleate on exposed areas of GaN. We have used this method to grow arrays of GaN nanowires that range from a single nanowire to one million nanowires. Due to the ability to accurately control nanowire diameter and location, we can apply optical Bragg scattering to simultaneously measure mechanical resonances of all the illuminated nanowires. GaN nanowires have unusually high mechanical quality factors for objects of their size and therefore small shifts in resonance frequency can be measured. Thus the arrays serve as compact, position-sensitive sensors for absorption or desorption of molecules and particles. By growing on silicon-on-insulator substrates, we have placed single nanowires onto wafers that can be fabricated into atomic force microscopy tips and demonstrated contact-mode operation, indicating the high mechanical strength of the nanowires and their bond to the substrate. In separate experiments, we have shown that GaN nanowires make superior tips for near-field scanning microwave microscopy and demonstrated electroluminescence from single p-n GaN nanowires with the core-sleeve geometry. Integration of these capabilities is ongoing with the goal of fabricating multifunctional scanning probes.

10114-44, Session 4

Metal-oxide-semiconductor plasmonic nanorod lasers *(Invited Paper)*

Shangjr Gwo, National Tsing Hua Univ. (Taiwan)

Scaling down semiconductor lasers in all three dimensions hold the key to the developments of compact, low-threshold, and ultrafast coherent light sources, as well as photonic integrated circuits. However, the minimum size of conventional semiconductor lasers utilizing dielectric cavity resonators (photonic cavities) is constrained to the diffraction limit. In the past few years, it has been experimentally demonstrated that the use of plasmonic cavities based on metal–oxide–semiconductor (MOS) structures can break this limit. In this presentation, I will report on the recent progress of plasmonic nanolasers using MOS structures. In particular, by using alloy-composition-varied indium gallium nitride/gallium nitride (InGaN/GaN) core–shell nanorods as the nanolaser gain media in the full visible spectrum, we are able to demonstrate full-color nanolasers that can be operated with ultralow CW lasing thresholds and single lasing modes. Full-color lasing in these subdiffraction plasmonic cavities is achieved via a unique autotuning mechanism based on a property of weak size dependence inherent in plasmonic nanolasers. As for choice of metals in the MOS structures, epitaxial Ag films and giant colloidal Ag crystals have been shown by us to be the superior constituent materials for plasmonic cavities due to their low plasmonic losses in the visible spectral range. Recently, we have also succeeded in developing InGaN/GaN nanorod array plasmonic lasers based on a metal (Au)-all-around MOS structure, which can be fabricated easily on a wafer scale. I will present the latest results in these developments.

10114-16, Session 5

Quantum optics with nanowires *(Invited Paper)*

Val Zwiller, KTH Royal Institute of Technology (Sweden)

Nanowires offer new opportunities for nanoscale quantum optics; the quantum dot geometry in semiconducting nanowires as well as the material composition and environment can be engineered with unprecedented freedom to improve the light extraction efficiency.

Quantum dots in nanowires are shown to be efficient single photon sources, in addition because of the very small fine structure splitting, we demonstrate the generation of entangled pairs of photons from a nanowire.

By doping a nanowire and making ohmic contacts on both sides, a nanowire light emitting diode can be obtained with a single quantum dot as the active region. Under forward bias, this will act as an electrically pumped source of single photons. Under reverse bias, an avalanche effect can multiply photocurrent and enables the detection of single photons.

Another type of nanowire under study in our group is superconducting nanowires for single photon detection, reaching efficiencies, time resolution and dark counts beyond currently available detectors. We will discuss our first attempts at combining semiconducting nanowire based single photon emitters and superconducting nanowire single photon detectors on a chip to realize integrated quantum circuits.

10114-17, Session 5

Nanoscale luminescence characterization of individual crystal phase quantum dots in ultrathin GaAs nanowires

Marcus Müller, Otto-von-Guericke Univ. Magdeburg (Germany); Peter Veit, Frank Bertram, Otto-von-Guericke-Univ. Magdeburg (Germany); Bernhard Loitsch, Julia Winnerl, Gregor Koblmueller, Jonathan J. Finley, Walter Schottky Institut, Technische Univ. München (Germany); Jürgen H. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

Crystal phase quantum dots embedded in nanowires (NW) have recently emerged as efficient single photon emitters. In particular, the formation of twin-plane defects in ultrathin GaAs NWs (diameter < 10 nm) leads to a quantum-dot like confinement of the excitons in all three directions. Using highly spatially resolved cathodoluminenscence spectroscopy (CL) directly performed in scanning transmission electron microscope (STEM), we will present a direct one by one correlation of the luminescence properties with crystal real structure of nanowire heterostructures.

The GaAs NWs have been produced by molecular beam epitaxy on a [111]-oriented Si-substrate. Subsequently, the GaAs NW diameter was reduced by a “reverse-reaction” process using in-situ thermal decomposition of the {110} side wall surfaces which leads typically to a diameter down to 7 nm. Finally, the NWs were overgrown by an AlGaAs passivation shell layer and a GaAs cap.

TEM investigations reveal a high density of disordered wurzite/zincblende structures in the bottom part of the nanowire whereas the upper part is dominated by the zincblende crystal phase containing few twin-plane defects. Highly spatially resolved CL measurements exhibit a blue shifted excitonic emission up to 1.55 eV as compared to bulk GaAs due axial quantum confinement effects of the ultrathin core. Addressing isolated twin-plane defects, we observe the formation of discrete sharp emission lines at ~1.60 eV which is attributed to an additional confinement effect of the excitons along axial direction. These crystal phase polytypism open the opportunity for the realization of homostructured quantum dot like emitters.

10114-18, Session 5

Influence of Droplet Size on the Growth of High-Quality Self-Catalyzed GaAsP Nanowires

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Self-catalyzed GaAsP NWs were grown on Si substrates by using MBE and demonstrated almost stacking fault free zinc blend crystal structure. By studying the influence of catalytic droplet size on the NW growth, Gibbs?Thomson effect is observed directly for the first time in the self-catalyzed NW growth mode. This effect can lower the effective supersaturation of the droplet, making smaller droplets exhibit slower growth rates and have higher P contents compared with those produced from larger ones. Therefore, this discovery provide a novel way to control the uniformity and composition of NWs. In addition, defect-free GaAs QDs have been successfully inserted into the GaAsP NWs. Without any surface protection layer, an exciton emission line width as narrow as 130 ?eV has been observed, which demonstrated great potential in the field of quantum information and nanophotonics. These results open up new perspectives for integrating III?V nanowire photovoltaics and visible light emitters on a silicon platform by using self-catalyzed GaAsP core?shell nanowires.

Zhang, Yunyan, et al. Nano letters 16.2 (2016): 1237

Zhang, Yunyan, et al. Nano letters 16.1 (2015): 504-511.

10114-19, Session 5

Band offsets in III-V nanowires determined by scanning tunneling spectroscopy *(Invited Paper)*

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Compound semiconductor nanowires (NWs) are promising building blocks for novel (opto)electronic and energy harvesting devices. Their efficiency depend critically on interfaces between different structural or compositional segments within III-V semiconductor NWs. Scanning tunneling spectroscopy (STS) is an ideal tool for the determination of band gaps and band offsets at interfaces, but thus far is mostly wrongly interpreted in literature: The commonly high step density at the sidewalls of III-V semiconductor NWs leads to extrinsic surface states pinning the Fermi energy within the fundamental band gap. Since the pinning level is different on every polytype and material composition, the relative band edge positions between different types of NW segments are extrinsically determined, but not by intrinsic band offsets. The extrinsic band offsets are much larger and likely have a stronger influence on the carrier transport than intrinsic band offsets. This problem is intrinsic to any surface sensitive characterization technique. Thus, we developed a new methodology to accurately determine band offsets between different NW segments by using a thin overgrown shell of

a material with a wider band gap which assures that the Fermi level pinning of both segments is identical. Tunneling through the thin shell probes the band edge position of the underlying core materials under defined pinning conditions, providing the intrinsic band offsets. We illustrate the physical effects on interfaces of wurtzite/zincblende GaAs and GaAsSb/GaAs NWs.

10114-20, Session 6

Structural and electronic properties of antiphase domains in GaP layers grown on Si(001) for integration in optoelectronics *(Invited Paper)*

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Epitaxial integration of III-V layers for optoelectronics on exactly oriented Si(001) substrates is of high interest and could be realized by using GaP as the starting III-V material. Due to the small lattice mismatch of GaP compared with Si it is used most commonly, but as all other III-V materials the growth of GaP on Si substrates leads to undesired antiphase domains. The boundaries of the antiphase domains are charged structural defects, reducing the device performance. In order to understand and thereupon reduce the formation of antiphase domains, detailed structural and electronical investigations are fundamental. Here, cross-sectional scanning tunneling microscopy (XSTM) and -spectroscopy is used to study antiphase domains and their electronic properties. XSTM is a very surface sensitive method and thus a powerful tool to distinguish between different atom species and reveal knowledge on the atomic arrangement of the antiphase boundaries. XSTM and XSTS data of antiphase domains with different spatial dimensions at the cross-sectional GaP/Si surface will be presented, indicating a size depending electronic effect of the antiphase domains compared with the GaP main phase. In addition, XSTM images were taken at different sample biases as well as at both sample polarities. Thus, we can systematically analyze the atomic arrangement of different antiphase boundaries and we will present detailed information discussing the physical properties of antiphase domains and their boundaries.

10114-21, Session 6

Optical characteristics of InAlAs/GaAlAs/GaAs quantum dots

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The type-I to type-II band alignment transition in InAlAsAs/AlGaAs/GaAs self-assembled quantum dots (QDs) is investigated when the Al-composition in QDs and barrier are changed. In particular, the In0.46Al0.54As/Ga0.46Al0.54As/GaAs QDs show unique optical properties. The PL peak energy has a blue-shift of >40 meV when the laser intensity increases by four orders of magnitude, indicating a type-II band alignment of the QDs. The formation of the type-II band alignment is explained by that the quantum-confinement effect pulls up the minimum electron energy level in the QDs and the ??X transition in the Ga0.46Al0.54As barrier. The time-resolved PL (TRPL) spectrum of QDs at peak wavelength exhibits a double-component decay behavior, suggesting the possibility of type-I and type-II band alignment coexistence in this QD sample. The continuum state of the QDs is also investigated. Emission associated with the continuum states of the QDs is directly observed in PL spectra. The PL excitation (PLE) and TRPL spectra reveal an efficient carrier relaxation from the AlGaAs barrier into the InAlAs QD ground state via the continuum states. The carrier recombination in the continuum states can compete with that in the QDs due to the long recombination lifetime in the type-II QDs. This feature of continuum state emission can not be observed for normal InGaAs/GaAs QDs with the type-I band structure.

10114-22, Session 6

Universal growth scheme for entanglement-ready quantum dots at telecom wavelength

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Quantum dots based on InAs/InP hold the promise to deliver entangled photons with wavelength suitable for the standard telecom window around 1550 nm, which makes them predestined to be used in future quantum networks applications based on existing fiber optics infrastructure. A prerequisite for the generation of such entangled photons is a small fine structure splitting (FSS) in the quantum dot excitonic eigenstates, as well as the ability to integrate the dot into photonic structures to enhance and direct its emission. Using optical spectroscopy, we show that a growth strategy based on droplet epitaxy can simultaneously address both issues.

Contrary to the standard Stranski-Krastanow technique, droplet epitaxy dots do not rely on material strains during growth, which results in a drastic improvement in dot symmetry. As a consequence, the average exciton FSS is reduced by more than a factor 4, which in fact makes all the difference between easily finding a dot with the required FSS and not finding one at all. Furthermore, we demonstrate that droplet epitaxy dots can be grown on the necessary surface (001) for high quality optical microcavities, which increases dot emission count rates by more than a factor of five. Together, these properties make droplet epitaxy quantum dots readily suitable for the generation of entangled photons at telecom wavelengths.

10114-23, Session 6

Highly ordered Ga(As)Sb quantum dots grown on pre-structured GaAs

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Ga(Sb)As quantum dots (QDs) are usually grown on unstructured GaAs substrates by self-organization in the Stranski-Krastanov mode. Here we report on Ga(As)Sb growth on a pre-structured GaAs substrate to achieve highly ordered QDs. Thus the area density can be controlled and the QDs laterally positioned.

The structure consists of arrays of holes milled with focused ion beam (FIB). For individual placements of single QDs it is very important that the diameter of the dots equals the diameter of the milled holes.

In a previous publication we have shown that we are able to change the diameter as well as the height of the QDs by controlled variation of growth temperature, Ga/Sb ratio, and nominal coverage.

The holes in the GaAs substrate are milled with a gallium FIB. The diameter, depth, and distance between the holes are varied. Also, different milling techniques are tested to optimize milling time and procedure.

Then the pre-structured GaAs substrate is overgrown in a molecular beam epitaxy (MBE) system. The growth is monitored by a reflectance anisotropy spectroscopy (RAS) system attached to the MBE unit.

Different sets of growth parameters are tested in combination with different milling parameters. With the optimum of both sets of parameters for structuring and growth the diameter of the QDs equals the size of the milled holes and the self-organized QDs can be grown highly ordered in the given pre-structured array. To the best of our knowledge this is the first work about exact positioning of Ga(As)Sb QDs on GaAs.

10114-24, Session 7

Low-temperature photoluminescence studies in epitaxially-grown GaAsN/InAs/GaAsN quantum-dot-in-well structures emitting at 1.31 um

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We report a single layer GaAsN/InAs/GaAsN quantum-dot-in-well (DWELL) structure with PL emission at 1.31µm important for applications in communication lasers. This extension has been achieved with a nitrogen composition of only 1.8% and QDs embedded within 1/6nm GaAsN which is higher compared to single layer QDs with GaAs and GaAsN capping layers as a result of confinement reduction on both sides of the QD energy levels. The structures remain as QDs till 800degC of annealing temperature alongwith a drastic enhancement in PL intensity as a result of annihilation of N-induced crystal defects which provide non-radiative recombination centers for carriers in the as-grown sample which is responsible for degraded luminescence. A typical highly asymmetric PL signature observed in dilute nitride structures is seen with a sharp cut-off at lower wavelengths and a large exponential tail at higher wavelengths in the as-grown and 650degC annealed samples. This is due to the presence of localized excitonic states extending into the bandgap close to the band edges. For higher annealing temperatures, this asymmetry disappears indicating an improvement in uniformity of nitrogen distribution and absence of localized states; which is also confirmed from a smaller blueshift in excitation intensity-dependent PL spectra of these samples. Well-resolved ground and first excited states in the PL spectrum of 700degC annealed sample indicates an improvement in QD confinement. Department of Science and Technology, Govt. of India and Riber, France are acknowledged.

10114-25, Session 7

Time-resolved photoluminescence study of magnetic CdSe/CdMnS/CdS core/multi-shell nanoplatelets

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Colloidal semiconductor nanoplatelets (NPLs) are quasi 2D-nanostructures that are grown and processed inexpensively using a solution based method and thus have recently attracted considerable attention. We observe two features in the photoluminescence spectrum, suggesting two possible recombination channels. Their intensity ratio varies with temperature and two distinct temperature regions are identified; a low temperature region (10K< T<90K) and a high temperature region (90K< T<200K). This ratio increases with increasing temperature, suggesting that one recombination channel involves holes that are weakly localized with a localization energy of 0.043?meV. A possible origin of these localized states are energy-variations in the xy-plane of the nanoplatelet. The presence of positive photoluminescence circular polarization in the magnetically-doped core/multi-shell NPLs indicates a hole-dopant exchange interaction and therefore the incorporated magnetic Manganese ions act as a marker that determines the location of the localized hole states [1]. Time-resolved measurements show two distinct timescales (?fast and ?slow) that can be modelled using a rate equation model. We identify these timescales as closely related to the corresponding recombination times for the channels. The stronger hole localization of one of these channels leads to a decreased electron-hole wave function overlap and thus a decreased oscillator strength and an increased lifetime. We show that we can model and understand the magnetic interaction of doped 2D-colloidal Nanoplatelets which opens a pathway to solution processable spin controllable light sources.

[1] Murphy, et. al. "Time-Resolved Photoluminescence Study of CdSe/CdMnS/CdS Core/multi-Shell Nanoplatelets." APL 108, 242406 (2016)

10114-26, Session 7

Local characterization of light trapping effects of metallic and dielectric nanoparticles in ultra-thin Cu(In,Ga)Se2 solar cells via scanning near-field optical microscopy

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Plasmonic and photonic nanostructures have proven beneficial for solar cell [1, 2]. By enhancing the light absorption through light trapping or scattering, nanostructures added in the absorber or at the interfaces not only improve the efficiency but also reduce the material consume, which is especially promising for solar cells using rare element in absorber. In order to apply more efficient nanotechnology in solar cell, it is necessary to recover the optical and electrical mechanism of efficiency enhancement from nanostructures. Here we investigate the optical interaction and the photon-electron generation between nanoparticles and absorber by a custom-built scanning near-field optical microscopy (SNOM). SNOM has proven to be a powerful tool for investigating optical properties of various surfaces in nanometer regime [3]. In this study, The near-field distribution of regular silver and dielectric nanoparticles on glass substrate and Cu(In,Ga)Se2 (CIGSe) produced by nanospheres lithography are characterized using SNOM, which give access to the optical mechanism of light trapping for solar cell. On the other hand, the photon-current of the CIGSe solar cell with and without nanostructures are studied with the SNOM recording the photon-electrons during surface scanning, which release the electric influence. In addition, Finite-Element-Method (FEM) Simulations have been performed to estimate a theoretical plasmonic enhancement factor (PEF) in both periodic particle geometry without scanning probe and SNOM geometry with a scanning probe. We found that the wavelength dependent PEF differs for different particle materials or sizes.

10114-27, Session 7

Investigating the influence of ligands on the surface-state emission of colloidal CdSe quantum dots

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Colloidal II-VI semiconductor quantum dots (QDs) are currently employed

in flat panel display technologies as they offer high luminescent quantum yields and narrow emissive linewidths while remaining inexpensive in comparison with epitaxial production methods. Under certain synthetic conditions, colloidal QDs can be made to be "dual-emitting" in which the QDs possess distinct "core" and "surface" excitonic states. Dual-emitting QDs are promising for the development of efficient solid state white-light emitting devices due to their broad surface emission (>200 nm). However, a lack of detailed understanding of the surface emission in these materials has impeded rational design of the surface properties. Recently performed single QD photoluminescence experiments suggest that the broad surface emission is due to strong electron-phonon interactions of a trapped surface exciton, which has been further supported by modelling based on Marcus-Jortner electron transfer theory. This paper investigates the surface dynamics in cadmium selenide QDs using resonance Raman and time-resolved photoluminescence techniques as a function of the surface composition of the QDs, which is varied through systematic ligand modification. The surface structure is further characterized through a number of spectroscopic techniques including solid state nuclear magnetic resonance and x-ray diffraction. The goal is to further elucidate the relationship between surface composition and emissive properties, as well as to improve current synthetic methodologies by identifying optimal types and ratios of surface ligands that maximize the photoluminescence quantum yield and quality of white light.

10114-9, Session PWed

The nonlinear optical properties of CdS quantum dots in phosphate glass

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The study of nonlinear optical properties is particularly important in laser active media since standing waves in lasers cavities produce self-focusing, temporal and spatial self-phase modulation and light-induced gratings that cause effects of hole-burning. In special quantum dots (QDs) are materials extensively investigated in the last years for their special physical properties associated to discrete energetic levels. Confinement effects make the QDs become promising materials, possessing unique optical properties such as tunable photoluminescence spectra with narrow bandwidth, high quantum yield, large multi-photon absorption cross section and fast-response nonlinear index. These properties of QDs lead to potential applications such as electronic and optical devices, chemical and biological sensors and optical energy transport.

It is well known that the Z-scan technique is appropriated to investigate nonlinear properties, where the nonlinear refraction and absorption can be investigated separately. This method utilizes a focused laser beam that is intense enough to access nonlinearities in a sample. In the last years, the Z-scan technique has been employed to investigate the nonlinear optical properties of a large number of materials including semiconductor QDs.

The aim of this work is therefore to use the Z-scan technique to determine the nonlinear refraction and nonlinear absorption of CdS doped phosphate glasses. This glass matrix, termed as PANK (P_2O_5-Al_2O_3-Na_2O-K_2O), was doped with 1, 2 and 3 % of CdS concentration.

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10114-28, Session PWed

Fabrication of diffraction gratings with electrically variable pitch and their effect on surface plasmon resonance

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Surface-relief diffraction gratings can be inscribed onto cast azobenzene molecular glass thin films by exposure to an interfering laser pattern at an absorbing wavelength. When coated with a thin metallic layer, surface plasmons can be exited at the interface between air and the metallic gratings. This plasmonic resonance can only be achieved when the incident light polarization is along the grating vector. The surface plasmon wavelength is dependent on many other parameters including the grating pitch, light incidence angle and the refractive indices of the surrounding media. When these azobenzene films were spin coated on electro-active substrates, such as an electrostrictive Lead Lanthanum Zirconate Titanate (PLZT) ceramic, the grating pitch was electrically varied when an in-plane electric field was applied. First, white light reflection scans were conducted and surface plasmon resonance was identified on two different test samples with grating pitches of 615 and 635 nm. Second, a sinusoidal electric field was applied on the PLZT substrate and a ten-fold signal increase was measured within a narrow 25 nm wavelength range in the reflected modulation signal, when locked on to twice the electric field frequency. These sharp peaks in the reflected modulation signals were explained using theoretical derivations stemming from the surface plasmon resonance condition and the electrostrictive theory of PLZT ceramic. This experiment successfully proved an electrically induced grating pitch variation leading to a subsequent shift in the plasmon wavelength.

10114-29, Session PWed

A simplified approach to Einstein's theories in size quantization

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The DMR has been studied for QWs, QWWs and QDs of III-V, IV-VI and II-VI compound materials under certain limiting conditions. It has been, taking QWs and QWWs and QDs of CdS , PbSe and InAs as examples, that the DMR decreasing film thickness and increases with increasing carrier degeneracy in various oscillatory manner emphasizing the influence of dimensional quantization uncaring cases. An experimental method for determining the DMR in QWs, QWWs and QDs having arbitrary dispersion laws has also been suggested.

10114-30, Session PWed

Nanogenerators based on organic and inorganic nanostructures

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Recently, the portable and wearable electronic devices, operated in the power range of microwatt to miliwatt, become available thank to the nanotechnology development and become an essential element for a comfortable life. Our recent research interest mainly focuses on the fabrication of piezoelectric nanogenerators based on smart nanomaterials such as zinc oxide novel nanostructure, M13 bacteriophage. In this talk, I will address a simple strategy for synthesizing the freestanding ZnO nanorodes/graphe/ZnO nanorods double sided heterostructure and fabricating the piezoelectric nanogenerator using such ZnO novel nanostructure. This novel nanostructure had the higher number density and specific surface area in a given area rather than those of epitaxial single heterostructure. Therefore, electrical outputs were improved up to 2 fold compared to those of single heterostructure. Further I will present the route for vertical alignment of M13 bacteriophage and the realization of piezoelectric nanogenerator based on vertically organized phage nanopillars.

10114-31, Session PWed

Light-emitting and photovoltaic devices based on quantum well-dots hybrid nanostructures

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We report on optoelectronic devices based on novel type of active region - quantum well-dots (QWD) hybrid nanostructures. This hybrid type of the active region can be described as a quantum well, which has an ultradense array of narrow-gap In-rich regions with the size of 10-20 nm, which serve as the localization centers of charge carriers. The QWD structures can be also considered as a uniform in size high-density dots array, where a lateral tunneling between individual dots as well as minibands formation is possible. Such QWD structures can be formed spontaneously during the MOCVD deposition of InxGa1-xAs (0.3< x<0.5) on GaAs substrate. The formation of 3D islands is promoted by using misoriented substrates and MOCVD growth at lowered temperature in a certain window of growth rates. Optimization of QWD growth parameters will be presented. The advantages of QWD were demonstrated in the microdisk lasers, where a singlemode lasing was achieved for microdisks with size as larger as 9 microns and also in the edge-emitting lasers, where QWD medium showed the decreased threshold current as compared to the reference quantum well laser and the higher gain in comparison with the quantum dot devices. The use of QWDs allowed us to expand the spectral range of GaAs single junction solar cells sensitivity in the long-wave optical region from 860nm up to 1100nm and provide a record high increase in the photocurrent, which is 4.6 mA/cm2 for the terrestrial and 5.2 mA/cm2 for the space spectrum.

10114-32, Session PWed

Delay characteristics comparison of coherently coupled high-Q multi-cavity array and single-embedded quantum-dot cavity systems

Serdar Kocaman, Gonul Turhan-Sayan, Middle East Technical Univ. (Turkey)

Recent demonstrations have showed that some effects which are known as quantum in origin also present in classical optics with a potential for variety of applications in many fields. One such field is the large-scale communications and an important subset of this area is about the on-chip optical interconnects and optical delay lines. The integrated implementations can provide scalability, low-power dissipation and large bandwidths in addition to the critical tunable delay lines for network reconfigurability. In this regard, it has been known that dynamic storage of light can be possible as a result of the quantum coherence in atoms leading to electromagnetically induced transparency (EIT) and more recent work revealed that EIT-like spectra and light trapping can also be observed with integrated cavity systems in an all-optical classical analog systems. In this work, the optical analogue to electromagnetically induced transparency is modeled for two separate systems with the same formalism and the spectral characteristics together with the generated group delay are compared. First system is a coherently coupled high-Q multi-cavity array which represents the classical EIT and is limited by the finite broadening of the cavity and the second one is a single embedded quantum dot (QD) cavity system, a cavity-QD EIT, that depends on both QD broadening and cavity properties. Similar spectral characters have been observed for both systems but the former generated theoretically two times higher group delays. Both configurations allow direct scalability for chip-scale optical pulse trapping and provide bases for coupled cavity quantum electrodynamics (CQED).

10114-33, Session PWed

Impact of varying barrier thickness on the optical characteristics of multilayer InAs/GaAs QDIPs

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An investigation of the optical properties of the multi stacked InAs quantum dot (QD) based photodetectors with changing capping layer thickness has been studied. There is an improvement in the QD structure and distribution due to InGaAs capping instead of GaAs capping. It is due to the inhibition of In-Ga intermixing and lesser In segregation towards the wetting layer in case of InGaAs capping. Here the combined InGaAs/GaAs capping layer thickness has been varied to investigate the effect of the vertical strain-coupling and QD size distribution.

All samples are grown by solid source molecular beam epitaxy with a V/III flux ratio of 50. A thickness variation in InGaAs/GaAs capping layer is done by keeping the total thickness constant at 12nm, 15nm, and 18nm. The ground state photoluminescence emission peak for the 3nm InGaAs capped QDs have pronounced redshift of 14nm, 32nm, and 36nm than the 2nm InGaAs capped QDs for the total capping layer thickness of 18nm, 15nm, and 12nm, respectively. It is observed due to better coupling in case of lower capping layer thickness and hence better dot size. Activation energy calculated from the temperature dependent photoluminescence study also gives an incremental trend with increase in coupling (18nm: 163.308meV, 15nm: 180.146meV, and 12nm: 215.53meV), which is attributed to lowering of QD ground state due to change in capping layer thickness. Hence the 12nm caped device with 3nm InGaAs capping gives better results probably due to better strain propagation. DST, India and RIBER, France are acknowledged.

10114-34, Session PWed

Characterisation of MOVPE InAs/GaAs QDs grown by MOVPE with and without strain balancing

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Applications of semiconductor quantum dots (QDs) include single photon sources, lasers for telecommunications, optical amplifiers for optical coherence tomography and solar cells for power generation. We report the development of metal organic vapour phase epitaxy (MOVPE) grown self-assembled InAs/GaAs QDs. The effects of growth parameters and close vertical stacking on the opto-electronic and structural properties are studied. We achieve control of the peak emission wavelength at room temperature from 1.19-1.27μm and control of the areal dot density from

0.4-3x1010cm-2. Significantly, a wavelength of 1.27μm and areal density of 3x1010cm-2 are simultaneously achieved. Stacking of QD layers to give large volumetric densities is important for the development of high gain/absorption material. Reducing the spacing thickness between QD layers increases the volumetric density but accumulated strain limits the separation to thicknesses greater than ~35nm. Smaller thicknesses can only be achieved by balancing the QD strain with material of opposite strain, e.g. GaAsP, with modelling of GaAs0.8P0.2 containing structures showing no detrimental effects on the electrical characteristics. Samples were grown with different QD layer separations down to 20nm both with and without 5nm GaAs0.8P0.2 strain balancing layers. X-ray diffraction analysis confirms the achievement of strain balancing. Electroluminescence shows improved performance for strain balanced devices with close vertical stacking. We demonstrate a strain balanced laser with a layer separation of 30nm and pulsed lasing at 50K with a threshold current density of 230-250A/cm2.

10114-35, Session PWed

A low-temperature investigation of the optical properties of coupled InAs quantum-dots with GaAsN/GaAs spacers

Akshay Balgarkashi, Mahitosh Biswas, Sandeep M. Singh, Debabrata Das, Indian Institute of Technology Bombay (India); Anuj Bhatnagar, Roshan L. Makkar, Nilesh Shinde, Society for Applied Microwave Electronics Engineering and Research (India); Subhananda Chakrabarti, Indian Institute of Technology Bombay (India)

Epitaxially-grown 10-layer coupled InAs quantum dots with GaAsN/GaAs barrier layers have been investigated. The PL spectra was seen to be a complex convolution of bimodal distribution of QDs alongwith an asymmetric signature introduced by incorporation of nitrogen into the structures. Reducing the GaAsN/GaAs barrier thickness (from 2/16nm to 2/8nm) resulted in an improvement of PL linewidth as low as 20meV of the dominant PL peak for the sample with thinnest barrier layer. A blueshift in emission was observed due to higher indium intermixing as a result of an increase in overall strain in the multilayer structure. The highly asymmetric exponential tail signature evident from the PL spectra of as-grown samples indicated a higher presence of localized N-induced excitonic states near the conduction band edge confirmed from excitation intensity-dependent PL spectra. The localized states were reduced in samples with thicker barriers which showed relatively lower asymmetry compared to samples with thinner barriers. Also, samples with thinner barriers showed an arrest in blueshift in the PL spectra with annealing temperature indicating thermal stability. DST, India and Riber, France are acknowledged.

10114-36, Session PWed

Refractory plasmonic nanostructures and devices for harsh environment applications

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Single crystalline transition metal nitrides (TMN) exhibit plasmonic behavior in the visible and near infrared regions. Ultra-thin, ultra-smooth epitaxial layers of TMNs provide unique solutions for some of the long-standing problems in the fields of plasmonics and metamaterials. Refractory properties of the material system enable the use of plasmonic elements under harsh environmental conditions such as extremely high temperatures. In this talk, we will present optical and material properties of titanium nitride (TiN) and zirconium nitride (ZrN). Thin films, lithographically fabricated nanostructures and colloidal samples are optimized for use in a variety of plasmonic applications. Well established material synthesis of oxides enables fabrication of large scale complex structures of refractory plasmonic materials via nitridation of titanium oxide nanoarchitectures. Self-passivating native oxide at the surface of TiN nanoparticle allows surface modification for controlled assembly. Our findings show that plasmonic TiN nanoparticles and their titanium oxide coating enable enhanced performance in plasmon assisted photocatalysis. Spectral position of the plasmon resonance of cubic TiN nanoparticles located in the biological transparency window in the near-infrared region makes it an interesting alternative plasmonic material for photothermal therapy.

10114-37, Session PWed

Efficient light extraction of site-controlled quantum-dots in nano-pyramidal structures

Sejeong Kim, Su-Hyun Gong, Jong-Hoi Cho, Yong-Hoon Cho, KAIST (Korea, Republic of)

Bright solid-state single-photon sources based on quantum dots (QDs) represent a key building block for quantum information technology. Obtaining high collection efficiency of single photons from QDs to predesigned optical waveguides or a free-space measurement setup is an important task for application of QDs to quantum information devices. Given that the collection efficiency of single photons from conventional QD embedded in a high index planar substrate is less than 5 %, there have been extensive efforts during the past decade to extract light efficiently using various photonics structures. However, most fabrication methods of photonics structures use a top-down approach and rely on chance, which results in an extremely low fabrication yield.

In this study, we propose that site-controlled QD in nanopyramidal structures can be utilized as unidirectional single-photon sources. Silver-coated nanopyramid structures grown by a lateral overgrowth technique cause the emission of QD to be guided in one direction. Furthermore, we demonstrate nanopyramid structures that can be detached from a substrate using an ultraviolet-curable optical adhesive material, thus having great potential in various applications. We observed highly directional single-photon emission from a QD in the detached inverted-pyramid structure. We would like to emphasize that this highly directional emission from the nanopyramid structure can easily be integrated with a photonic waveguide system with high coupling efficiency.

10114-38, Session PWed

Non-linear two-photon resonance fluorescence of a single artificial atom

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Resonance fluorescence that arises from the interaction of a coherent light field with a two level system, has led to the development of numerous physical breakthroughs in atomic quantum optics. Increasing the complexity of the physical systems, first predictions for a non-linear counterpart of resonance fluorescence were made theoretically already 30 years ago [1].

In this contribution, we present non-linear resonance fluorescence studies for the two-photon excitation [2, 3] of individual semiconductor quantum dots. Upon monitoring the population evolution for increasing Rabi frequencies we observe an s-shaped behavior as a clear signature of the non-linear excitation process. We model the non-linearly driven artificial atom as a 4-level system resonantly excited on a two-photon resonance and

find excellent agreement between experiment and theory. The simulations reveal the crucial role of the environmental coupling to LA-phonons of the system leading to a redistribution of the population between the levels. Finally, we directly measure the formation of dressed states in the non-linearly driven system that emerge from the resonant two-photon interaction between the coherent light field and the 4-level artificial atom, the hallmark of two-photon resonance fluorescence [4]. Our results open the route for investigating a range of optical phenomena from entangled photon pairs to photon bundles resulting from the coherent non-linear interaction in two-photon resonance fluorescence [5].

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10114-41, Session PWed

Biosensing characteristics of InAs nanowire transistors grown by MOCVD

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Semiconductor nanowires (NWs) have been one of the more active research areas, due to their distinct physical properties that can lead to various optical and electrical applications. Moreover, NWs as a biosensor membrane have been applied for the accurate detection of biological interactions in bio-chemical sensing and environmental monitoring areas. It has many major features, such as high sensitivity, real time detection, and non-labeling. Biosensors based on ion-sensitive field-effect transistors (IS-FETs) using NWs have been developed because of the large surface-to-volume ratio of NWs. IS-FETs exhibit a conductance change in response to variations in the electric field or potential at the conduction channel surface due to the binding of biomolecules. Here, we demonstrated IS-FETs based on NWs with different diameters and doping concentration to obtain the high sensitivity and various applications. The growth of the catalyst-free InAs NWs was carried out using a horizontal reactor MOCVD system (AIXTRON Inc.). A p-type Si (111) wafer (? = 1 -10 ?-cm) was prepared for the NW growth. Here, NWs with diameters of around 50 ~ 150 nm were grown and the doping concentration also was changed around x±10e16~18 /cm2. IS-FETs with the grown InAs NWs were fabricated using the photolithography and the lift-off process. The sensing characteristics have been investigated through studying the gate response of the NW conductance in different ambient conditions. The sensitivities of IS-FETs with the grown InAs NWs are measured with various ethanol solutions. More detailed results will be presented.

10114-42, Session PWed

Silicon nanoparticles fabrication for near- and mid-infrared scattering

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Recently, plasmonic fractal-like structures have been determined to enhance photovoltaic device performances; indeed, through an efficient coupling of the incident light at different frequency bands into both the surface plasmon modes and the cavity modes, a broadband absorption enhancement can be accomplished.

Currently, silicon nanoparticles (SiNPs) are of great interest due to their potential applications in various fields such like optoelectronics, microelectronics, photonics, photovoltaics, chemical, and biologic sensors. SiNPs. become the most important and well-known semiconductor because Si-based devices have dominated microelectronics for many decades. Indeed, the production of smart SiNPs. materials to enhance absorption and light scattering is currently the most convenient approach.

The size tunable optical and electronic properties of silicon nanoparticles have made them became great potential for fabrication of engineering materials especially for light emitting diodes, chemical sensor and quantum dot laser.

However, several methods have been developed for the synthesis of silicon nanoparticles such as chemical etching, sol-gel technique, laser ablation, sputtering process, hot-wire synthesis, ball milling process, and microemulsion.

In our method the effect of the reduction agent concentration (sodium borohydrate $NaBH_4$) on the properties of silicon nanowires synthesized via microemulsion route is reported. In this work, the concentration of the silicon tetrachloride ($SiCl_4$) with polyethylene glycol (PEG) as a surfactant and sodium hydroxide (NaOH) as stabilizer, are keep fixed. Two samples with varied concentration of $NaBH_4$ from 0.20 M to 0.30 M were synthesized. It was found that the highest concentration of $NaBH_4$ gave better formation of silicon nanoparticles.

10114-43, Session PWed

Analytical study of optical activity of chiral-shape nanocrystals

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During their fabrication, semiconductor nanocrystals often develop various surface defects, which make them adopt chiral shapes and become optically active. The chiral imperfections of individual nanocrystals, even if they are small compared to the nanocrystal size, can introduce a significant asymmetry in the interaction of the nanocrystal ensemble with left circularly polarized light and right circularly polarized light. It is therefore of both practical and fundamental significance to be able to calculate analytically the strength of optical activity induced by the irregularities of the nanocrystal shape.

Here, we present a simple quantum-mechanical model describing optical activity of semiconductor nanocuboids with chiral shape irregularities. Our model can be used to treat a wide variety of real chiral nanocrystals, including nanorods with Eshelby twists, nanoplatelets with corners bent in opposite directions, and helix-shape quantum dots. Using the developed model, we calculate the rotatory strengths and dissymmetry factors of intraband transitions in various kinds of chiral nanocrystals and show that the lattice-constant deviations of their shapes from a perfect nanocuboid can result in optical activity, which is 10-100 times stronger than that of typical chiral molecules. We also show that among nanocrystals of the same material, nanorods and nanoplatelets feature the strongest shape-induced optical activity, while quantum dots are least affected by the surface defects.

The developed approach can be used to study chiral nanoparticles other than nanocuboids, and the results of our study may prove useful in various branches of biomedicine, nanophotonics, and chemistry.

10114-45, Session PWed

Selective-area growth of InAs nanowire arrays on Si3N4/Si(111) by molecular beam epitaxy

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InAs nanowires have good optical properties due to their low bandgap energy, high electron mobility and low ohmic contact resistivity [1]. When directly integrated on the cost-effective silicon substrates, they show great prospects in fabricating high-performance, next-generation infrared photoelectronics [2]. Selective-area-epitaxy eliminates foreign seed particle contamination, and enables precise control over nanowire size, position and directionality, which improves the performance predictability of large-scale nanowire arrays devices [1]. Moreover, the one-dimensional structure of a nanowire solves the problem of large lattice mismatch of InAs heteroepitaxy on Si (11.6%) by elastically relaxing near the nanowire surface [1, 2].

In this study, catalyst-free, position-controlled InAs nanowires were grown on silicon by molecular beam epitaxy, and the growth kinetics dependence on nanohole diameter and interwire distance was investigated. The selective-area growth of nanowires was realized by implementing an electron beam patterned silicon nitride mask. Temperature, V/III ratio and hydrofluoric acid etch time were varied to find the optimal growth selectivity and yield. It is found that the nanowire diameter stays relatively constant with different nanohole pitch and diameter. In addition, growth of self-induced InAs nanowires on silicon was demonstrated, and their morphology dependence on temperature and fluxes was studied.

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10114-46, Session PWed

Nanoscale chemical imaging with photo-induced force microscopy

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Infrared Photo-induced Force Microscopy (IR PiFM) is based on an atomic force microscopy (AFM) platform that is coupled to a widely tunable mid-IR laser. PiFM measures the dipole induced at or near the surface of a sample by an excitation light source by detecting the dipole-dipole force that exists between the induced dipole in the sample and the mirror image dipole in the metallic AFM tip. This interaction is strongly affected by the optical absorption spectrum of the sample, thereby providing a significant spectral contrast mechanism which can be used to differentiate between chemical species. Due to its AFM heritage, PiFM acquires both the topography and spectral images concurrently and naturally provides information on the relationship between local chemistry and topology. Due to the steep dipole-dipole force dependence on the tip-sample gap distance, PiFM spectral images have spatial resolution approaching the topographic resolution of AFM, demonstrating sub 10 nm spatial resolution on a variety of samples. PiFM spectral images surpass spectral images that are generated via other techniques such as scanning transmission X-ray microscopy (based on synchrotron source), micro confocal Raman microscopy, and electron microscopes, both in spatial resolution and chemical specificity. The breadth of the capabilities of PiFM will be highlighted by presenting data on various organic, inorganic, and low dimensional materials. By enabling imaging at the nm-scale with chemical specificity, PiFM provides a powerful new analytical method for deepening our understanding of nanomaterials and facilitating technological applications of such materials.

10115-1, Session 1

Interference and nanoimprint lithography for the patterning of large areas *(Invited Paper)*

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Interference lithography (IL) is the best suited technology for the origination of large area master structures with high resolution. The seamless patterning of areas of as large as 1.2 x 1.2 m? could be demonstrated with periodic features, i.e. a hexagonal grating with a period of 1 μm. An argon ion laser emitting at 363.8 nm was applied for this process, allowing for periods in the range of 100 μm to 200 nm.

In order to replicate master structures, we make use of nanoimprint lithography (NIL) processes. There, we employ three toolings with different operation principles for UV-NIL, ranging from conventional to in-line capable roller processes. The soft PDMS stamps exhibit a high adaptability to rough and wavy surfaces and can even be applied to imprint on thin silicon wafers (<50 μm) without damaging the substrate. A critical parameter for the further up-scaling of NIL is the lifetime of these stamps. One reason for their degradation is the diffusion of resist into the PDMS. We introduce AFM force-distance measurements as method to characterize degradation and a thermally assisted UV-NIL process in combination with resists of more complex molecular structure to considerably increase the stamp lifetime.

In photovoltaics different concepts like the micron-scale patterning of the front side as well as the realisation of rear side diffraction gratings are presented. The benefit for each is shown on final device level. In the context of display and lighting applications, we realised various structures ranging from designed, symmetric or asymmetric, diffusers, antireflective and/or antiglare structures, polarisation optical elements (wire grid polarisers), light guidance and light outcoupling structures.

10115-2, Session 1

Manufacturing of polymer optical waveguides using self-assembly effect on pre-conditioned 3D-thermoformed flexible substrates

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Optical data communication is increasingly interesting for many applications in industrial processes. Therefore mass production is required to meet the requested price and lot sizes. Polymer optical waveguides show great promises to comply with price requirements while providing sufficient optical quality for short range data transmission. A high efficient fabrication technology using polymer materials could be able to create the essential backbone for 3D-optical data transmission in the future.

The approach for high efficient fabrication technology of micro optics described in this paper is based on a self-assembly effect of fluids on preconditioned 3D-thermoformed polymer foils. Adjusting the surface energy on certain areas on the flexible substrate by flexographic printing mechanism is presented in this paper. With this technique conditioning lines made of silicone containing UV-varnish are printed on top of the foils and create gaps with the exposed substrate material in between. Subsequent fabrication processes are selected whether the preconditioned foil is coated with acrylate containing waveguide material prior or after the thermoforming process. Due to the different surface energy this material tends to dewet from the conditioning lines. It acts like regional barriers and sets the width of the arising waveguides. With this fabrication technology it is possible to produce multiple waveguides with a single coating process. The relevant printing process parameters that affect the quality of the generated waveguides are discussed and results of the produced waveguides with width ranging from 10 to 300 μm are shown.

10115-3, Session 1

Partial etch phase (PEP) optical elements for high-volume applications

Thomas W. Mossberg, Dmitri Iazikov, LightSmyth Technologies, Inc. (United States)

An optical surface providing for pointwise control over transmitted or reflected phase can form the basis of a wide range of optical devices including lenses, vortex plates, splitters, diffusers, etc. Whilst traditional fabrication technologies can limit the spatial phase control achievable, the continuing development of IC production tools has pushed the spatial resolution obtainable to significantly less than Datacom (~ 850 nm) and Telecom (~1550 nm) wavelengths. We have developed a subwavelength design and fabrication approach that utilizes the power of IC fabrication tools, e.g. photolithographic steppers/scanners, and binary etch to demonstrate general point-specific phase-shifting devices such as Lenses, lens arrays, vortex plates, and lens + vortex plates. Measured performance will be reported. Owing to the mass production capability of modern IC production tools, PEP devices are cost effective, which combined with their high functionality renders them significant new entrants into the collection of existing beam forming devices.

PEP structures (comprised of partially etched substrate or overlayer surfaces) are configured so that within each wavelength-scale region a fraction of material (or equivalently the surface area since the etch is binary) is removed in proportion to the phase shift locally desired. The depth of etch is typically set to provide a 2ϖ phase difference between rays propagating through etched and unetched regions. In the subwavelength limit, the actual optical signal averages phases over etched and non-etched regions producing a controllable net local output phase. Minimization of scattering and unwanted diffractive losses is discussed.

10115-5, Session 1

Biomimetic hairy surfaces as superhydrophobic highly transmissive films for optical applications

Felix Vuellers, Guillaume Gomard, Jan B. Preinfalk, Efthymios Klampaftis, Matthias Worgull, Bryce S. Richards, Hendrik Hölscher, Maryna N. Kavalenka, Karlsruher Institut für Technologie (Germany)

Combining high optical transmission, water-repellency and self-cleaning is of great interest for optoelectronic devices operating in outdoor conditions, such as photovoltaics where shading can significantly reduce the power output. The surface of water plant Pistia stratiotes combines these functionalities through a dense layer of transparent microhairs. It renders the surface superhydrophobic without affecting absorption of sunlight necessary for photosynthesis. Inspired by this surface, we fabricated a superhydrophobic flexible thin nanofur film made from optical grade polycarbonate using a scalable combination of hot embossing and hot pulling techniques. During fabrication, heated sandblasted steel plates locally elongate softened polymer, thus covering its surface in microcavities surrounded by high aspect ratio micro- and nanohairs. The superhydrophobic nanofur exhibits contact angles of (166±6°), low sliding angles (<6°) and is self-cleaning against various contaminants.

The overall transmission of the self-standing nanofur film stands above 85% over the visible range, with 97% of the transmitted light scattered forward. Reflection drops below 4% when coated on a polymeric substrate, which can enhance light extraction in organic light emitting diodes (OLEDs). We report an increase of more than 10% in luminous efficacy for a nanofur coated OLED compared to a bare device. Finally, the nanofur film can be used for enhancing the incoupling of light to solar cells, while additionally providing self-cleaning properties. Optical coupling of the nanofur to a multi-crystalline silicon solar cell results in a 5.8% gain in photocurrent compared to a bare device under normal incidence.

10115-6, Session 2

Inorganic nanomembranes for quantum photonics and optoplasmonics *(Invited Paper)*

Oliver G. Schmidt, Leibniz IFW Dresden (Germany)

Nanomembranes are thin, transferable and can be shaped into almost arbitrary geometries. We embed high quality quantum emitters into III-V semiconductor nanomembranes and transfer them onto piezoelectric substrate actuators. By applying external piezoelectric stress, the quantum properties of single photon emitters can be accurately tuned and major steps towards a viable quantum communication technology have been reached. We also strain engineer thin SiOx based nanomembranes and shape them into fully integratable microtubular microcavities. These novel microarchitectures show photonic spin-orbit coupling, controlled coupling of surface plasmons to optical resonator modes as well as a high compatibility to new 3D integration schemes.

10115-7, Session 2

Deterministic control of the emission from light sources in 1D nanoporous photonic crystals *(Invited Paper)*

Juan F. Galisteo-López, Consejo Superior de Investigaciones Científicas (Spain)

Controlling the emission of a light source demands acting on its local photonic environment via the local density of states (LDOS). Approaches to exert such control on large scale samples, commonly relying on self-assembly methods, usually lack from a precise positioning of the emitter within the material. Alternatively expensive and time consuming techniques can be used to produce samples of small dimensions where a deterministic control on emitter position can be achieved.

In this work we present a full solution process approach to fabricate photonic architectures containing nano-emitters which position can be controlled with nanometer precision over squared milimiter regions. By a combination of spin and dip coating we fabricate one-dimensional (1D) nanoporous photonic crystals, which potential in different fields such as photovoltaics or sensing has been previously reported, containing monolayers of luminescent polymeric nanospheres.

We demonstrate how, by modifying the position of the emitters within the photonic crystal, their emission properties (photoluminescence intensity and angular distribution) can be deterministically modified. Further, the nano-emitters can be used as a probe to study the LDOS distribution within these systems with a spatial resolution of 25 nm (provided by the probe size) carrying out macroscopic measurements over squared milimiter regions. Routes to enhance light-matter interaction in this kind of systems by combining them with metallic surfaces are finally discussed.

10115-8, Session 2

Integration of 3D printed dome-shaped lens with InGaN light-emitting diodes with enhanced light extraction efficiency

Yu Kee Ooi, Christopher Ugras, Shaunak Gandhi, Denis Cormier, Jing Zhang, Rochester Institute of Technology (United States)

III-nitride based light-emitting diodes (LEDs) have been extensively employed in wide variety of applications due to their higher efficiency and longer lifetime. However, further improvement in the LED external quantum efficiency, which depends on internal quantum efficiency and light extraction efficiency (?_exe), is essential for LED application as next generation high-efficiency light sources. It is well-known that conventional planar structure InGaN LED suffers from total internal reflection due to large refractive index contrast between GaN (n_GaN = 2.5) and air (n_air = 1), which results in low ?_exe (~4%). Accordingly, various approaches such as surface roughening and microstructure arrays have been investigated to enhance the ?_exe. Nevertheless, most of these proposed methods involve elaborated fabrication methods which add up extra steps during large scale production.

In this work, we proposed the integration of three-dimensional (3D) printing with LED fabrication as a cost-effective, straightforward, and highly-reproducible method to improve the ?_exe. Specifically, a 5-mm diameter dome-shaped lens is 3D-printed layer-by-layer, with layer thickness of 25 ?m, using optically transparent acrylate-based photopolymer on planar structure blue-emitting LEDs, followed by UV curing with 405 nm laser beam. Then, the 3D-printed lens is post-cured in UV curing oven for ~30 minutes. The refractive index of the printed lens has been characterized as ~1.5 in the visible spectrum regime. Our simulation results based on 3D finite-difference time-domain method show that up to 1.61-times enhancement in ?_exe can be achieved by the use of 3D-printed lens of various dimensions as compared to conventional planar structure.

10115-9, Session 2

LOPA-based direct laser writing of multi-dimensional and multi-functional photonic submicrostructures

Fei Mao, Quang Cong Tong, Dam Thuy Trang Nguyen, Thi Huong Au, Rache Odessey, Florent Saudrais, Ngoc Diep Lai, Ecole Normale Supérieure de Cachan (France)

We have developed a simple and low-cost fabrication technique, based on low one-photon absorption (LOPA) phenomena in a weakly absorbing photoresist (532 nm laser versus SU8 photoresist). This novel approach enables production of submicrometer 2D and 3D structures and could allow for imaging of submicrometer structures in 3D using a very modest laser power [1,2]. This technique is also demonstrated as a simple technique to couple a single nanoparticle (nonlinear, metallic, or fluorescent) to polymer-based photonic structures [3,4]. It is recently demonstrated that the LOPA based direct laser writing also allowed to realize as desired plasmonic (gold) and magneto-photonic (Fe3O4) nanostructures. Different applications of these fabricated structures could be envisioned, and partially realized, such as tuneable photonic devices, data storage, bright single photon source, quantum information.

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10115-10, Session 3

Hybrid metal-dielectric nanostructures for advanced light-field manipulation *(Invited Paper)*

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All-dielectric and plasmonic nanostructures have complementary advantages regarding their capabilities for controlling light fields at the nanoscale [1]. While all-dielectric nanostructures can provide near-unity efficiency, plasmonic nanostructures are more compact and offer strong near-field enhancement. Combination of photonic nanostructures of both types offers a promising route towards compact optical elements that unify low absorption losses with small footprints, while at the same time providing a high versatility in engineering the optical response of the hybrid system towards specific functionalities.

This talk aims to review our recent progress in coupling designed plasmonic nanoantennas to high-index dielectric nanostructures. Following a general analysis of coupling of plasmonic and high-refractive-index dielectric nanoresonators, various specific hybrid nanostructure designs will be discussed.

For the fabrication of designed hybrid metal-dielectric nanostructures we use a two-step electron-beam lithography (EBL) procedure [2]. The first step of EBL is used in combination with reactive-ion etching to define the dielectric nanostructures. The second step of EBL is followed by evaporation of gold and a lift-off process, and serves to define the plasmonic elements. Between the two steps, a precision alignment procedure is performed in order to allow for the precise positioning of the gold nanostructures with respect to the silicon nanostructures.

Using this approach, we realize and optically characterize various hybrid metal-dielectric nanostructures designed to support a range of novel functionalities, including directional emission enhancement [2] and on-chip light routing.

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10115-11, Session 3

Control of spectral transmission enhancement properties of random anti-reflecting surface structures fabricated using gold masking

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Random anti-reflecting subwavelength surface structures (rARSS) have been shown to suppress Fresnel reflection and scatter from optical surfaces. The structures effectively function as a gradient-refractive-index at the substrate boundary, and the spectral transmission properties of the boundary have been shown to depend on the structure statistical properties (diameter, height, and density.) We fabricated rARSS on fused silica substrates using gold masking. A thin layer of gold was deposited on the surface of the substrate and then subjected to a rapid thermal annealing (RTA) process at various temperatures. This RTA process resulted in the formation of gold “islands” on the surface of the substrate, which then acted as a mask while the substrate was dry etched in a reactive ion etching (RIE) process. The plasma etch yielded a fused silica surface covered with randomly arranged “rods” that act as the anti-reflective layer. We present data relating the physical characteristics of the gold “island” statistical populations, and the resulting rARSS “rod” population, as well as optical scattering losses and spectral transmission properties of the final surfaces. We focus on comparing results between samples processed at different RTA temperatures, as well as samples fabricated without undergoing RTA, to relate fabrication process statistics to transmission enhancement values.

10115-12, Session 3

New fabrication technique for nanoporous gold nanoparticles

Fusheng Zhao, Md Masud Parvez Arnob, Wei-Chuan Shih, Univ. of Houston (United States)

Nanoporous gold nanoparticles (NPG-NP) showcase tunable pore and ligament sizes ranging from nanometers to microns. The nanoporous structure and sub-wavelength nanoparticle shape contribute to its unique LSPR properties. NPG-NP features large specific surface area and high-density plasmonic field enhancement known as “hot-spots”. Hence, NPG-NP has found many applications in nanoplasmonic sensor development. In our recent studies, we have shown that NPG-NP array chip can be utilized for high-sensitivity detection by various enhanced spectroscopic modalities, as photothermal agents, and for disease biomarker detection.

To date, array-format, substrate-bound NPGN has been fabricated by either colloidal nanosphere lithography or random nucleation during the sputtering deposition process. Although highly cost-effective, these techniques cannot provide precise control of individual particle size and location. In this paper, we report the development of a new fabrication technique based on electron-beam lithography (EBL).

Herein, a customized EBL technique is utilized to pattern larger areas (several square millimeters) of randomly distributed NPGN by careful design of the shot pattern, which limits the writing time to the acceptable level. Since the position, size, and shape of a huge number of features need to be generated and stored individually, memory limitations of this unique EBL technique constitutes an additional challenge, which is normally not present if small areas are to be patterned with features on an ordered lattice. This issue is solved by programmatically generating random feature positions within a simulation cell of carefully chosen size and implementing periodic boundary conditions.

10115-14, Session 4

Optical fiber plasmonic lens for near-field focusing fabricated through focused ion beam

Karen Sloyan, Henrik Melkonyan, Marcus S. Dahlem, Masdar Institute of Science & Technology (United Arab Emirates)

Plasmonic lenses, based on the excitation of surface plasmon polaritions (SPP) at the metal-dielectric boundary, can produce subwavelength spot sizes and field enhancement effects. Near-field focusing can be achieved using plasmonic lenses illuminated by linearly, circularly or radially polarized light. In this work, we report on numerical simulations and fabrication of an optical fiber plasmonic lens for near-field focusing. The lens consists of an Archimedean spiral structure defined on the tip of a SM600 optical fiber (single-mode operation at 633 nm), coated with a 100 nm-thick Au layer. Through three dimensional finite-difference time-domain (FDTD) computations, the relative intensity of the center lobe is maximized as a function of the number of spiral turns and radial distance of the first turn (inner radius). Numerical results for a 0.1 μm inner radius show that, as the number of turns increases from two to twelve, the maximum value of the relative intensity increases ~2.2 times. A reduction of the intensity is observed when the inner radius is increased. The optimized plasmonic lens produces a full width at half maximum (FWHM) of ~180 nm, beyond the diffraction limit. The lens was fabricated through focused ion beam milling, using 30 keV accelerated Ga+ ions, with a probe current of 30 pA. The resulting lens is a left-hand twelve-turn spiral structure with an inner radius of 0.1 μm, a slit width of 0.2 μm and ~15.5 μm outer diameter. The lens can find applications in scanning near-field optical microscopy, sensing and optical trapping.

10115-15, Session 4

Metal free structural colors via disordered nanostructures with nm resolution and full CYMK color spectrum

Marcella Bonifazi, Valerio Mazzone, Andrea Fratalocchi, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Engineering colors through optical properties of nanostructures represents a research area of great interest, due to the many applications that can be enabled by this technology, from adaptive camouflage to micro-images for security and biomimetic materials. The state of the art technology is represented by the use of metallic periodic structures of 140nm, which can create a limited number of colors of the spectrum.

In this work we introduce a new approach, based on a fully metal-free technique that takes advantage from the complex scattering of disordered structures created by a three-dimensional process with EBL (electron beam lithography). Engineering the scattering from complex media already demonstrated to be a successful in creating ultra-black material and new type of sources for optical applications.

Our new approach realizes the fundamental colors of the CMYK (Ciano, Magenta, Yellow and Black) system, and therefore is able to represent any color in the spectrum, including variations in intensity. The resolution of each pixel is limited by the EBL only, ranging in the nm scale. With this technique, we can print substrates as simple as silicon with the resolution of 158760 dpi. This method is interesting in the field of micro-security, due to the impossibility of counterfeiting a random, three-dimensional pattern of pixels created on a transparent dielectric material that cannot be imaged via electron imaging such as SEM (scanning electron microscope).

We will discuss the fabrication detail of this color printing technique, many examples of applications and the approaches for large-scale fabrication through nanoimprinting lithography.

10115-17, Session 5

Elastomeric phase masks, transfer stamps, and assembly platforms: Fabrication methods for unusual micro/nano-optical systems *(Keynote Presentation)*

John A. Rogers, Univ. of Illinois at Urbana-Champaign (United States)

Research over the last decade has led to the emergence of several powerful methods for micro/nanofabrication, with direct relevance to optics and optoelectronic systems. This talk summarizes some of our contributions to this field, through the development techniques that use (1) conformal phase masks for photodefining 3D structures with applications in photonic crystals, (2) rubber transfer stamps for integrating inorganic semiconductor materials on plastic substrates for solid state lighting, emissive displays and efficient photovoltaics, and (3) stretchable assembly platforms for controlled transformation of 2D precursor structures into well-defined, complex 3D architectures for optical MEMS. In each case, we review the basic operating principles and provide some examples of enabled applications in optics and optoelectronics.

10115-18, Session 5

3D laser lithography: Quo vadis? *(Keynote Presentation)*

Martin Wegener, Karlsruher Institut für Technologie (Germany)

3D printing on the macroscale is a huge trend worldwide. Ultimately, one would like to 3D print anything, including complete functional devices. Apart from boosting printing speed and pushing spatial resolution to the nanometer scale, 3D printing of many different materials poses a major challenge. In 2D graphical printers, thousands of different colors can be printed from just three color cartridges. By analogy, future 3D printers may print thousands of effective (meta-)materials from just a few materials cartridges. These metamaterials should not only be tailored in terms of their optical properties, but also electrical, magnetic, thermodynamic, mechanical, and bio-chemical.

10115-19, Session 5

Fabrication and properties of porous silicon and silica 3D gradient refractive index micro-optics *(Keynote Presentation)*

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

Via electrochemical etching of silicon, followed by materials conversion, 3D gradient refractive index micro-optics were formed. Elements including flat lenses, Bragg mirrors, polarization sensitive optical splitters and structures with nearly arbitrary refractive index distributions were formed with a particular focus on micro-optics important for solar energy harvesting. The conversion from silicon to silica and titania enabled the optics to operate in the visible with minimal loss, something particularly important for solar energy harvesting applications.

10115-20, Session 5

Advanced fabrication for complex nanooptics and metamaterials *(Keynote Presentation)*

Harald Giessen, Univ. Stuttgart (Germany)

Advanced fabrication techniques have contributed majorly in the advance of nanooptics, metamaterials, and plasmonics. Particularly complex nanophotonic devices and functionalities such as sensing, polarization control, nonreciprocity, and nonlinearity benefited from advanced fabrication. One key element is multilayer electron-beam lithography and multilayer stacking. This allows for the fabrication of 3-dimensional structures, where the upper layer can add functionality through coupling. Furthermore, multilayer lithography allows for the combination of different materials which can also give additional functionality. A premier example is the combination of a high-quality gold nanoantenna with a palladium nanodisk closeby, which allows for nanoantenna-assisted gas sensing.

When the second layer adds some elements such as highly nonlinear materials, for example some semiconductor dot being placed in the gap of gold nanoantennas, additional functionality arises from this combination as well. Tuning the nanoantennas to the infrared, resonant antenna-enhanced vibrational sensing which is particularly specific to molecular fingerprints becomes possible.

Apart from electron beam lithography, also advanced fabrication techniques such as colloidal hole lithography, angled evaporation, as well as the use of direct laser writing for 2D structures enables new avenues in combining new shapes, complex structures, and the resulting functionality.

In the same realm, micro- and nanooptics can be combined, allowing for example very efficient in- and outcoupling of quantum dots to the far field, for example by nanoantenna arrays and other optical elements.

10115-21, Session 6

Directed assembly of colloidal particles for micro/nano photonics *(Invited Paper)*

Yuebing Zheng, The Univ. of Texas at Austin (United States)

Bottom-up fabrication of complex structures with chemically synthesized colloidal particles as building blocks pave an efficient and cost-effective way towards micro/nano photonics with unprecedented functionality and tunability. Novel properties can arise from quantum effects of colloidal particles, as well as inter-particle interactions and spatial arrangement in particle assemblies. Herein, I discuss our recent developments and applications of three types of techniques for directed assembly of colloidal particles: moiré nanosphere lithography (MNSL), bubble-pen lithography (BPL), and optothermal tweezers (OTTs). Specifically, MNSL provides an efficient approach towards creating moiré metasurface with tunable and multiband optical responses from visible to mid-infrared regime. Au moiré metasurfaces have been applied for surface-enhanced infrared spectroscopy, optical capture and patterning of bacteria, and photothermal denaturation of proteins. BPL is developed to pattern a variety of colloidal particles on plasmonic substrates and two-dimensional atomic-layer materials in an arbitrary manner. The laser-directed microbubble captures and immobilizes nanoparticles through coordinated actions of Marangoni convection, surface tension, gas pressure, and substrate adhesion. OTTs are developed to create dynamic nanoparticle assemblies at low optical power. Such nanoparticle assemblies have been used for surface-enhanced Raman spectroscopy for molecular analysis in their native environments.

10115-22, Session 6

Laser-assisted dealloying for direct-write patterning of plasmonic nanostructures

Jingting Li, Fusheng Zhao, Wei-Chuan Shih, Univ. of Houston (United States)

Recently, nanoporous gold (NPG) has attracted significant interest due to its unique properties such as large specific surface area, bi-continuous nanostructure, high electrical conductivity and the applicability of thiol-gold surface chemistry. Patterned NPG disks showcase tunable pore and ligament sizes ranging from nanometers to microns. The nanoporous structure and sub-wavelength nanoparticle shape contribute to its unique LSPR properties. NPG disk not only features large specific surface area, but high-density plasmonic field enhancement known as "hot-spots". Hence, NPG disks have found many applications in nanoplasmonic sensor development. In our recent studies, we have shown that NPG disks array chip can be utilized for high-sensitivity detection by various enhanced spectroscopic modalities, as photothermal agents, and for disease biomarker detection.

To date, patterned NPG disks have been exclusively fabricated by colloidal nanosphere lithography. Starting with pattern transfer into alloy disks, dealloying subsequently turns the alloy disks into NPG disks. In this paper, we present another NPG patterning method by localized laser heating, during which dealloying occurs at the laser focal spots due to elevated temperature. This approach has enabled us to pattern NPG entity with various sizes and shapes. We have investigated fabrication parameters such as laser power, irradiation duration, and solution environment. We have also characterized the plasmonic resonance of the patterned NPG disks by extinction spectroscopy. The noncontact nature of this technique is well suited for the processing of substrates immersed in an aqueous environment. Further, this technique shares the same advantages as maskless laser direct writing.

10115-23, Session 8

Multi-photon microfabrication of three-dimensional capillary-scale vascular networks *(Invited Paper)*

Mark A. Skylar-Scott, Harvard Univ. (United States) and Massachusetts Institute of Technology (United States); Man-Chi Liu, Yuelong Wu, Massachusetts Institute of Technology (United States); Mehmet F. Yanik, Massachusetts Institute of Technology (United States) and ETH Zürich (Switzerland)

Human tissues are replete with dense microvascular networks to enable perfusion of nutrients to cells, and biomimetic models of microvasculature could enable the study of complex cellular behavior at the capillary level. However, existing 3D printing methods for generating perfusable microvasculature are limited in resolution, and fail to recapitulate the microscale geometry of capillaries. Here, we describe a method to rapidly multiphoton microfabricate collagen scaffolds to generate a directly perfusable, freeform, biomimetic, and branched three-dimensional microvascular network in collagen. When endothelial cells are added to the scaffolds, they migrate through the patterned channels to form an intact, confluent endothelium with luminal diameters as small as 15 microns, similar to those of native capillaries. Furthermore, we present a method for multiphoton micropatterning homing ligands into specific regions of a capillary network. By combination of microvascular geometry and micropatterned cues, we study the homing of leukocytes to specific sites in a microvascular network. This method can enable the construction of in vitro assays with precisely defined microarchitecture and micropatterned chemical cues for studying cellular behavior at the capillary level.

10115-24, Session 8

3D STED lithography: Protein binding and non-binding

Richard Wollhofen, Johannes Kreutzer, Eljesa Murtezi, Bianca Buchegger, Johannes Kepler Univ. Linz (Austria); Jaroslaw Jacak, Johannes Kepler Univ. Linz (Austria) and Upper Austria Univ. of Applied Sciences (Austria); Thomas A. Klar, Johannes Kepler Univ. Linz (Austria)

Stimulated emission depletion (STED) lithography can be used for the assembly of acrylic structures down to several tens of nanometers. Protein adhesive acrylates allow manufacturing of nano-confined, protein functionalized structures. The structures show good biocompatibility and allow an easy bio-functionalization with proteins, even down to a single protein level.[1, 2] Some acrylates, specifically those containing polyethylene-glycol (PEG) are inert against protein adhesion. This allows designing 3D compound structures of different acrylate polymers with different adhesion properties for biomolecules. However, the reasons for adhesion or non-adhesion remain unclear; possibly they are of electrostatic or hydrophilic/phobic nature. A much more elegant and more controlled way of protein functionalization would be to include functional groups such as thiols or carboxyl-groups. In initial experiments, we used multi-functionalized zirconium-oxo clusters[3] to provide covalent binding functionality to acrylate structures. Going beyond these initial experiments, we report on other strategies to bind proteins to nanoscale spots either via biotin-streptavidin or via covalent bonding using thiol or carboxyl groups, atop of protein repellent 3D scaffolds. Possible use of such structures includes three dimensional biosensors or scaffolds to anchor proteins otherwise mobile in membranes for cell-physiological research.

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10115-25, Session 8

Process Development for High-Resolution 3D-Printing of Bioresorbable Vascular Stents

Henry Oliver T. Ware, Adam C. Farsheed, Robert Van Lith, Evan Baker, Guillermo Ameer, Cheng Sun, Northwestern Univ. (United States)

Tens of thousands of Americans die each year from complications caused by narrowed arteries. Metal and polymer stents are employed to apply internal pressure to reopen narrowed arteries. However, the commercially available vascular stents made with general sizes often fail to provide optimal fitting that accommodate individual patient's anatomical difference. We recognize that the emergence of 3D printing technology may offer the highly desirable capabilities to design and fabricate patient-specific bio-absorbable stents. In this work, we report the development of a high-resolution continues projection microstereolithography (cPuSL) process and the matching photopolymers that collectively enables 3D printing of bioresorbable vascular Stents. A methacrylated polydiolcitrate was synthesized and formulated into a bioresorbable, antioxidant B-InkTM. B-InkTM is polymerizable was used for fast 3D printing of completely customizable stents using cPuSL. Stents achieved a lateral resolution of 7.1 x 7.1 um^2, with a curing thickness of 20 um. A 20 mm length stent was printed in approximately 70 minutes and had adequate strength. The mechanical properties of 3D-printed stents with struts of 150 um and walls thickness of 500 um were comparable to those of a control bare metal Nitinol stent. Furthermore, 3D-printed stents are fully customizable and they could be compressed and self-expanded within a clinically relevant time frame upon deployment. Upon deployment, the 3D-printed stent can significantly improve the mechanical properties of a pig artery. These results are a significant step forward toward on-the-spot and on demand patient-specific stent manufacture.

10115-26, Session 8

Fabrication and characterization of multi-point side-firing optical fiber by laser micro-ablation

Hoang Nguyen, Fusheng Zhao, Jingting Li, Wei-Chuan Shih, Univ. of Houston (United States)

Compared to traditional optical fibers, which are designed to transmit light from one end to the other, a multi-point side firing optical fiber can be useful in several applications such as phototherapy, optogenetics brain stimulation and remote sensing. We present the fabrication and characterization of an optical fiber capable of launching light from virtually any point along its circumferential surface by laser micro-ablation. Continuous wave (CW) laser radiation was employed to form a conical-shaped cavity (side window) in the fiber core. Because of the total internal reflection, when the laser beam reached the side window-outside medium interface, the beam was reflected to the side of the optical fiber. A single side window on 730 ?m fiber can deliver more than 8% of the total coupled light. Light-firing output can be increased to more than 19% by using femtosecond (fs) laser ablation on smaller optical fiber (65 μm). In addition, the fiber also exhibited 3-dimensional light emission by placing side-windows of various orientations on its axis.

We envision the 65 um-OD multi-point side-firing optical fiber to be employed in optogenetics brain neuron stimulation in vivo. To test the feasibility of this approach, ablated fibers were investigated in agar-based tissue mimicking material (0.5% w/v in water). Successful multi-point side-firing capability has been demonstrated in the tissue phantom with similar refractive index. Furthermore, this experiment was also used to test the side-firing fiber's mechanical strength in order to optimize the window's depth.

10115-27, Session 8

Nanostencil lithography with scanning optical fiber tip

Raquel Flores, Ricardo Janeiro, Dionisio A. Pereira, Jaime Viegas, Masdar Institute of Science & Technology (United Arab Emirates)

In this work, nanolithographic patterning by means of a nanostencil inscribed on an optical fiber tip is presented. One-shot registration of multiple-sized features within a 4 ?m diameter patterning circle has been experimentally tested on photoresist AZ5214E coated silicon substrate, with features as small as 160 nm beign obtained, replicating the original stencil with excellent agreement.

The nanostencil was created by focused ion beam (FIB) milling, although other techniques such as femtosecond laser ablation or pattern transfer to fiber tip can also be employed. Stencils can be arbitrary or based on optical elementary designs such as line patterns, photonic crystals, Fresnel zone plates or photon sieve. Exact transfer of the inscribed pattern is obtained while in contact lithography, while proximity exposure enables complex modulation of the optical near-field by the phase and/or amplitude stencil mask. This allows for optical interference to occur, in full 3D space, rendering sub-wavelength spot focusing, annular pattern formation, as well as the formation of 3D complex shapes.

Experimentally, a 405 nm laser beam with 17 mW power was launched into the core of UV-Visible single mode fiber (S405-XP) on which end a

photon sieve was previously inscribed by FIB. This tip was scanned over the photoresist. Patterning consisted of 1D scans, for which a minimum line width of 350 nm was obtained. Additionally, step-and-repeat patterning of the photon sieve fiber tip stencil was performed with, all features down to 160 nm being clearly resolved. The results find application in nanopatterning of photoelectrodes for water splitting.

10115-28, Session 9

Two-photon polymerization as a structuring technology in production: Future or fiction? *(Invited Paper)*

Emely Marie Harnisch, Fraunhofer-Institut für Produktionstechnologie IPT (Germany); Robert Schmitt, Fraunhofer-Institut für Produktionstechnologie IPT (Germany) and RWTH Aachen Univ. (Germany)

Two-Photon Polymerization (2PP) has become an established structuring technology since it was first realized by Sun et al. in 1999. Due to its high degree of freedom and its high resolution beyond the diffraction limit, it opens up novel possibilities with regard to structure design. Serving very different applications like optics and photonics, biology or microfluidics, the technology allows for fully three dimensional, individual and complex geometries with improved and diverse functionalities.

Within the context of manufacturing, properties like efficiency, velocity and an easy integration into process chains move into focus. To overcome the slow writing speed of 2PP the two different approaches of multi beam writing and molding were adopted by several research groups. Since process chains based on a structured master and molding are already established when manufacturing different kinds of optical elements, it is obvious to use structures made with 2PP as a master for molding. Even though, the design is limited to 2.5 dimensions by the molding process, 2PP offers more possibilities concerning the structure geometry than traditional technologies like lithographic or cutting ones.

By means of some optical structures with relevant functionalities, designed by various companies, different criteria with regard to a production chain were evaluated: The shape accuracy when writing with 2PP, the moldability with injection molding and PDMS as well as the measurability with different measurement techniques. Beside proposals for process chains based on 2PP for manufacturing optical elements, an approach for molding biological structures will be presented briefly.

10115-29, Session 9

Progress in fabrication of waveguide spatial light modulators via femtosecond laser micromachining

Nickolaos Savidis, Sundeep Jolly, Bianca Datta, MIT Media Lab. (United States); Michael G. Moebius, Harvard Univ. (United States); Thrasyvoulos Karydis, MIT Ctr. for Bits and Atoms (United States); Eric Mazur, Harvard Univ. (United States); Neil Gershenfeld, MIT Ctr. for Bits and Atoms (United States); V. Michael Bove Jr., MIT Media Lab. (United States)

We have previously introduced a femtosecond laser micromachining-based scheme for the fabrication of anisotropic waveguides in lithium niobate for use in a guided-wave acousto-optic spatial light modulator. This spatial light modulation scheme is extensible to off-plane waveguide holography via the integration of a Bragg reflection grating. In this paper, we present femtosecond laser-based direct-write approaches for the fabrication of (1) waveguide in-coupling gratings and (2) volume Bragg reflection gratings via permanent refractive index changes within the lithium niobate substrate. In combination with metal surface-acoustic-wave transducers, these direct-write approaches allow for complete fabrication of a functional spatial light modulator via femtosecond laser direct writing.

10115-30, Session 9

Strategies for rapid and reliable fabrication of microoptical structures using two-photon polymerization

Sönke Steenhusen, Sebastian Hasselmann, Gerhard Domann, Fraunhofer-Institut für Silicatforschung ISC (Germany)

In recent years two-photon absorption-based laser lithography processes also known as direct laser writing or two-photon polymerization (2PP) have attracted broad interest. This is due to the generation of microoptical elements with topographies not feasible using conventional process technologies. High design flexibility and attainable precision achievable by 2PP, combined with application-specific materials, such as, hybrid polymers, enable new levels of functional Integration. Thereby, several novel applications can be addressed in the future.

2PP relies on focusing femtosecond laser pulses into a photopolymer thus confining the solidification of the material to the focal volume. This provides true 3D capability and non-diffraction limited resolution due to threshold processes.

During fabrication, the entire volume of the desired 3D structure has to be filled by a point-by-point approach. In consequence, to adopt 2PP as an additive manufacturing technique at an industrial level throughput has to be increased.

Here we discuss the optimization of 2PP regarding process time and topographical specifications such as achievable feature size and accuracy. In this context, different application scenarios in refractive and diffractive microoptics are reviewed.

The application of galvoscanner technology is of particular interest due to potentially 100 x faster positioning velocities. We demonstrate how this enables the fabrication of large but also extremely precise structures in short times. Simultaneously, the effects on the photochemistry of the processed material during 2PP are investigated.

Another promising strategy for mass production of 2PP enabled structures is the fabrication of molds. Replication techniques of 2PP written master structures using nanoimprint lithography approaches are demonstrated.

10115-31, Session 9

The development of a piezoelectric polymer-based photo-curable resin for 3D printing process

Evan Baker, Weishen Chu, Henry Oliver T. Ware, Adam C. Farsheed, Cheng Sun, Northwestern Univ. (United States)

We present in this work the development and experimental validation of a new piezoelectric material (V-Ink) designed for compatibility with projection stereolithography additive manufacturing techniques. Piezoelectric materials generate a voltage output when a stress is applied to the material, and also can be actuated by using an external voltage and power source. This new material opens up new opportunities for functional devices to be developed and rapidly produced at low cost using emerging 3D printing techniques. The new piezoelectric material was able to generate 115mV under 1N of strain after being polled at 80°C for 40 minutes and the optimal results had a piezoelectric coefficient of 105x10^(-3)V.m/N. The current iteration of the material is a suspension, although further work is ongoing to make the resin a true solution. The nature of the suspension was characterized by a time-lapse monitoring and through viscosity testing. The potential exists to further increase the piezoelectric properties of this material by integrating a mechanical to electrical enhancer such as carbon nanotubes or barium

titanate into the material. Such materials need to be functionalized to be integrated within the material, which is currently being explored. Printing with this material on a “continuous SLA” printer that we have developed will reduce build times by an order of magnitude to allow for mass manufacturing. Pairing those two advancements will enable faster printing and enhanced piezoelectric properties.

10115-32, Session 9

Novel seamless origination and tooling approaches for film imprinting technologies

Jörg Mick, Volkmar Boerner, Christoph Stoever, Thomas Ruhl, Philip Mück, Oliver Humbach, temicon GmbH (Germany)

Industrial applications such as lighting, display, solar and life science are facing a high demand of micro- and nanostructures to functionalize surfaces on films and on components. Preferably those structures show a high level of quality and are available on very large formats. And with respect to economic efficiency, the tools used for the surface texturing in industrial roll-to-roll or roll-to-plate processes don´t even show any seamline in order to reduce the offcut towards a minimum.

For the fabrication of nanostructures on very large formats Interference Lithography is a well-known and established technology. Structures with features sizes down to 100nm could be realized almost on one square meter. For large structure dimensions of several ten micrometer UV-Lithography is used to functionalize surfaces. We also established this technology on rather large areas. Since more than one year we are now working intensively on transferring both of those technologies onto curved, convex surfaces. So far step-and-repeat approaches have been investigated, resulting in homogeneous patterns without visible seams. Novel continuous exposure approaches are under investigation and should also be transferred towards drum lengths of more than one meter.

However, it is necessary to take care for the complete process chain and not only for the origination of micro- and nanostructures. Therefore we present the latest developments including tooling as well as roll-imprinting processes of final products. By covering all process steps within the full chain, all single steps and involved materials could be adapted to each other in order to ensure high quality films.

10115-33, Session 10

Ultrafast laser 3D lithography for rapid prototyping of pure cross-linkable materials at a nanoscale *(Invited Paper)*

Mangirdas Malinauskas, Linas Jonu?auskas, Darius Gailevicius, Sima Rek?tyt?, Vilnius Univ. (Lithuania)

Here I will cover how both linear and non-linear light interactions can result to a precise spatially-controlled meso-scale processing of polymer materials. This can be employed for diverse applications, namely rapid prototyping of: microoptics, nanophotonics, and tissue engineering. A special emphasis on single-photon and multi-photon processes followed by an avalanche ionization and subsequent thermal accumulation will be figured in. It will be highlighted which specific phenomena can be advantageous for tunable material properties modifications at different degrees in all three-dimensions (3D). Plasmon assisted free-form lithography will be shown superseding the photosensitizing species inside a pre-polymer material. Furthermore, employing sub-picosecond pulsed light a 3D nanolithography of pure (non-sensitized) cross-linking materials will be demonstrated. This in turn opens vast opportunities for production on demand of transparent integrated micro-optical components, high laser-energy resistant nanophotonic devices, and finally - non-cytotoxic bio-scaffolds for pre-clinical research.

Lastly, lithography with polarization structured light will be shown enabling precise tuning of voxel dimensions at a nanoscale. This novel finding will be emphasized for its extreme importance towards 3D photonic applications. In addition, soft-lithography will be proposed as a method to upscale the fabrication throughput, as well as maskless laser lithography fabrication of soft-molds will be introduced for reducing one sequence step of a standard procedure.

10115-34, Session 10

Direct-laser metal writing of surface acoustic wave transducers for integrated-optic spatial light modulators in lithium niobate

Nickolaos Savidis, MIT Media Lab. (United States); Michael G. Moebius, Harvard Univ. (United States); Bianca Datta, Sundeep Jolly, V. Michael Bove Jr., MIT Media Lab. (United States); Eric Mazur, Harvard Univ. (United States)

Recently, the fabrication of high-resolution silver nanostructures using a femtosecond laser-based direct write process in a gelatin matrix was reported. The application of direct metal writing towards feature development has also been explored with direct metal fusion, in which metal is fused onto the surface of the substrate via a femtosecond laser process. In this paper, we present a comparative study of gelatin matrix and metal fusion approaches for directly laser-written fabrication of surface acoustic wave transducers on a lithium niobate substrate for application in integrated optic spatial light modulators.

10115-35, Session 10

Realisation of 3D metamaterial perfect absorber structures by direct laser writing

Vygantas Mizeikis, Ihar Fanyaeu, Shizuoka Univ. (Japan)

We report design, fabrication and optical properties of 3D electromagnetic metamaterial structures for perfect absorption (PA) at mid infra-red frequencies. The absorber consists of single-turn metallic helices arranged in a periodic two-dimensional array. This architecture enables realisation of polarisation-invariant resonant perfect absorption within a considerable range of incidence angles. Unlike the conventional planar metamaterials consisting of metallic ground plane and alternating dielectric and metallic layers, our absorber is all-metallic, and in principle does not require metallic ground plane, which permits optical transparency at frequencies away from the perfect absorption resonance. The samples were designed for operation at mid-infrared frequencies taking into account lattice geometry, unit cell size, and dielectric dispersion of the metal used. Dielectric templates of the samples were fabricated by femtosecond direct laser write technique in photoresist, and subsequently metallized using gold sputtering. The samples were found to exhibit resonant absorption in excess of 90% at the resonant wavelength of 7.7?m in accordance with expectations. Fast prototyping of perfect absorber metamaterials demonstrated by this study may contribute to development of novel structures for infrared energy harvesting and conversion, as well as narrow-band thermal detection and emission.

10115-36, Session 10

Automated aberration compensation in high numerical aperture systems for arbitrary laser modes

Julian Hering, Erik H. Waller, Technische Univ. Kaiserslautern (Germany); Georg von Freymann, Technische Univ. Kaiserslautern (Germany) and Fraunhofer Institute for Physical Measurement Techniques (IPM) (Germany)

Since a large number of optical systems and devices are based on differently shaped focal intensity distributions (point-spread-functions, PSF), the PSF's quality is crucial for the application's performance. E.g., optical tweezers, optical potentials for trapping of ultracold atoms as well as stimulated-emission-depletion (STED) based microscopy and lithography rely on precisely controlled intensity distributions. However, especially in high numerical aperture (NA) systems, such complex laser modes are easily distorted by aberrations leading to performance losses. Although different approaches addressing phase retrieval algorithms have been recently presented[1–3], fast and automated aberration compensation for a broad variety of complex shaped PSFs in high NA systems is still missing.

Here, we report on a Gerchberg-Saxton[4] based algorithm (GSA) for automated aberration correction of arbitrary PSFs, especially for high NA systems. Deviations between the desired target intensity distribution and the three-dimensionally (3D) scanned experimental focal intensity distribution are used to calculate a correction phase pattern. The target phase distribution plus the correction pattern are displayed on a phase-only spatial-light-modulator (SLM). Focused by a high NA objective, experimental 3D scans of several intensity distributions allow for characterization of the algorithms performance: aberrations are reliably identified and compensated within less than 10 iterations.

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10115-37, Session 10

Nanostructures for highly efficient infrared detection

Darius Gailevicius, Vilnius Univ. (Lithuania); Zeki Hayran, TOBB Univ. of Economics and Technology (Turkey); Mirbek Turduev, TED Univ. (Turkey); Hamza Kurt, TOBB Univ. of Economics and Technology (Turkey); Saulius Juodkazis, Swinburne Univ. of Technology (Australia) and Melbourne Ctr. for Nanofabrication (Australia); Mangirdas Malinauskas, Vilnius Univ. (Lithuania); Vygantas Mizeikis, Shizuoka Univ. (Japan); Kestutis Staliunas, Univ. Politècnica de Catalunya (Spain) and Institució Catalana de Recerca i Estudis Avançats (Spain)

We propose a high sensitivity photodetection tool at near-infrared frequencies, based on a novel principle of slowed- and stopped-light in chirped 3D photonic nanostructures. The main goal is to substantially increase the efficiency of absorption and provide chromatic resolution in infrared radiation detection.

The basic idea is that in specially designed photonic structures, in particular in chirped photonic crystals, the light slows down and "stops" at particular positions along the structure, before it reflects back [1,2]. The intensity of light is strongly enhanced at the position where it stops, therefore the stopped light can be very efficiently absorbed. This design offers a possibility of enhanced photodetection. Moreover, the light components of different frequencies stop at different positions along the crystal, which enables absorption and photodetection with chromatic resolution.

The idea is being developed under a NATO SPS project "Nanostructures for Highly Efficient Infrared Detection", 2016-2018. Different ingredients of the design are being developed by the groups of consortium: the concept of the stopped light and increased absorption; the 3D micro/nano-fabrication of photonic artificial materials [3]; and control of absorption by nano-patterned thin films [4], and others.

In the presentation we will describe the physics of the basic idea, will provide analytical estimations of the effect and its numerical proof, and we will report on the technical progress – the fabrication of 3D photonic nanostructures, embedding of the graphene absorbers, and the first measurements of chromatically resolved absorption.

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10115-38, Session 10

Nonlinear polymer/quantum dots nanocomposite for two-photon nanolithography of photonic devices

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Optical technology of data transfer (OTDT) has the advantage over electronic data transfer due to the higher speed and less losses. However the bottleneck of OTDT, which restricts its application is the absence of fast all-optical switchers. One of the way to implement all-optical switching is the use of nonlinear Kerr effect - local modification of refractive index by intense laser beam.

Direct laser writing is a unique method of laser manufacturing, allowing both high resolution and the ability for 3D structuring. Unfortunately, third order susceptibility of conventional photoresists is not large enough to produce significant Kerr effect and thus implement all-optical switching.

Nanocrystal quantum dots are known to possess large nonlinear optical properties and processes leading to non resonant nonlinearity are relatively fast which make them excellent candidates for all-optical switching. Unfortunately quantum dots cannot be assembled into arbitrary form.

In our work we present a composite based on CdSe quantum dots with photocrosslinkable surface groups and commercial photoresist SU-8. It has been shown that quantum dots are homogeneously dispersed in polymer matrix. Nonlinear optical susceptibility of the resin has been measured by Z-scan technique for different quantum dots concentrations and the material has been structured via direct laser writing.

10115-39, Session PWed

Laser nanolithography and pyrolysis of SZ2080 hybrid for slowing light in 3D photonic crystals

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Application of heat treatment has been used for creating silicon 3D photonic crystals, where a preform is created from an all-organic polymer (SU-8), which is in turn filled through a multistep process with silicon and the organic part is removed [1]. Alternatively, the selective removal of the organic part from organic-inorganic materials (e.g. Ormocer) through pyrolysis was demonstrated to be advantageous for the reduction of lattice dimensions [2]. This can be exploited for photonic bandgap structures or mechanically ultra-strong glassy carbon structures [3].

In this presentation, the implementation of femtosecond laser direct write 3D lithography technique in combination with the thermal post-treatment for photonic applications using an organic-inorganic sol-gel resist is given [4]. We start with a direct-laser write (DLW) structuring of ultra-low shrinkage SZ2080 hybrid Si and Zr containing polymer and follow by a hard bake reducing into an inorganic spatially shrunk 3D structure. In our case, we advance the technique by applying SZ2080 material and employing a single step post-process to produce a 3D photonic crystal with sub-micrometer scale features. The preprocess structure is of woodpile configuration with a transverse period of 0.35 μm, longitudinal period of 1 μm of 4 stacks. Heating is performed in Ar gas environment in temperature ranges from 300 to 600°C and variable time intervals up to 6h. A repeatable and homogeneous scaling down of the primal dimensions up to 60% is observed. We show the possibility of employing such a technique to produce slow-light based devices for the IR and VIS wavelength regimes [5].

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[3] J. Bauer, Approaching theoretical strength in glassy carbon nanolattices, Nat. Mater 15, 438–443 (2016).

[4] M. Malinauskas et al., Ultrafast laser processing of materials: from science to industry, Light: Sci. Appl. 5, e16133 (2016).

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10115-40, Session PWed

Fabrication of electro-wetting liquid lenticular lens by using diffuser

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Liquid lenticular multi-view system has great potential of three dimensional image realization. This paper aims to introduce a novel fabrication method of electro-wetting liquid lenticular lenses using diffuser. The liquid lenticular device consists of a UV adhesive chamber, two immiscible liquids and a sealing plate. The diffuser makes UV light spread slantly not directly to negative photoresist on a glass substrate. In this process, Su-8, the suitable material to fabricate a structure in high stature, is selected for negative photoresist. After forming a Su-8 chamber, the UV adhesive chamber is made through a PDMS sub-chamber that is made from the Su-8 chamber. As such, this research shows a result of a liquid lenticular lens having slanted side walls with an angle of specific degrees. The UV adhesive chamber having slanted side walls is more advantageous for electro-wetting effect achieving high diopter than the chamber having vertical side walls. After that, gold is evaporated for electrode, and parylene C and Teflon AF1600 is deposited for dielectric and hydrophobic layer respectively. For two immiscible liquids, DI water and a blend of 1-Chloronaphthalene and dodecane with specific portions are used. Two immiscible liquids are injected in underwater environment and a glass that is coated with ITO on one side is sealed by UV adhesive. The completed tunable lenticular lens can switch two and three dimensional images by using electro-wetting principle that changes surface tensions by applying voltage. Also, dioptric power and operation speed of the liquid lenticular lens array are measured.

10115-41, Session PWed

Antireflection coatings for non-planar optical surfaces by atomic layer deposition

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Most optical systems contain a large number of lenses or other optical elements. Reflection losses on each interface reduce the intensity of the transmitted light and hence the overall efficiency of the system. These reflection losses can be drastically reduced by applying anti-reflection (AR) coatings to the optical surfaces. Commonly, thin films applied in precision optics are produced by physical vapor deposition (PVD). However, on strongly curved surfaces thickness gradients can occur when using PVD, thus the required film thickness will not be meet, leading to an attenuation of the desired antireflection of single- or multilayer AR coatings.

Atomic layer deposition (ALD) is an alternative and very promising method that inherently offers a high reproducibility, large-area thickness uniformity and conformal coating on structured substrates with high aspect ratio. This cycle-controlled deposition technique is based on self-limiting surface reactions. Due to the surface-controlled growth a uniform film thickness on highly curved surfaces is expected.

We present the optical properties, e.g. spectral range of transparency, optical homogeneity and refractive index, of different dielectric metal-oxides deposited by ALD. In this work, two approaches are demonstrated to reduce the reflection losses at optical surfaces by ALD. First we demonstrate AR coatings that are based on multi-layer stacks using SiO_2 as low refractive index material, as high-index material we investigated HfO_2, TiO_2 and Ta_2O_5. Secondly, we show single-layer AR coatings using nano-porous SiO_2 layers with tunable refractive indices that are prepared by ALD and selective etching.

10115-42, Session PWed

Bioresists from renewable recourses as a sustainable photoresins for 3D laser microlithograhy: Material synthesis, cross-linking rate, and characterization of the structures

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The commercially available resins are not cheap and of limited applicability, often of unknown chemical ingredients and fixed to certain mechanical properties [1]. In our researches, it is important to have bioresin appropriate to 3D print micro-scaffolds for cell proliferation and tissue engineering. Thus the primary chosen substance for photosensitive material synthesis glycerol diglycidyl ether which can be obtained from renewable recourses. Glycerol diglycidyl ether polymers can be applied as a sustainable photoresins [2]. Chosen composition was following: glycerol diglycidyl ether, 3,4-epoxycyclohexylmethyl-3,4-epoxycyclohexane carboxylate (30 mol %), photoinitiator (mixture of triarylsulfonium hexafluoroantimonate salts, 50 % in propylene carbonate, 3 mol %). UV lithography was employed to determine its photocross-linking rate and processed material properties. Small droplets of the composition were casted on the glass. The hydrophilic interaction between glass surface and droplets was strong enough to keep the samples upside-down. It ensures adhesion of the formed structure after exposition to the surface. After exposing material to UV radiation of 365 nm wavelength through a micro-patterned amplitude mask selective photopolymerization was observed. An acetone was used as a solvent to dissolve UV unaffected area and highlight formed microstructures. The materials were classified according to their: photoreactivity, photomodification selectivity, mechanical rigidity, developing and adhesive properties. The resin was compared to FormLabs Form 1+ standard materials, namely Form Clear and AutoDesk Ember PR48. The results show that glycerol diglycidyl ether based composition is less photosensitive, thus it requires prolonged exposure, more powerful light source or additional photoinitiator. It motivates to continue studies photoresins from renewable recourses towards 3D laser microlithography applications.

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[2] S. Kasetaite et al., Polym. Bull. 72:3191–3208 (2015)

10115-43, Session PWed

Two-stage evaporated ordered nanoporous ultrathin metal films using reusable template

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Metal nanostructured films still attract widespread attention due to their unique properties and function compared to their bulk counterparts. Metal nanostructured films have been fabricated by various techniques, the method of anodic alumina template was used, but the detaching of the metal films and anodic alumina template would damage the metal films. In this work, we present a method for depositing ordered nanoporous ultrathin metal films onto reusable anodic alumina template by two-stage thermal evaporation. The metal (aluminum or nickel) was evaporating at a higher template temperature (typically ?80ºC) in the first step, followed by evaporation at a relatively lowered temperature (typically ?35ºC) in the second step. This process led to the deposited film of the second step detached from the deposited film of the first step because of different temperature. The pure ultrathin metal film of the second step was fabricated successfully, meanwhile the anodic alumina template with the deposited film of the first step were reusable. The characterizations of SEM indicate that both of obtained aluminum film and nickel film have the hexagonal morphology similar to anodic alumina template. The relevant parameters for the successful preparation were investigated. This novel fabrication method not only simplifies the preparation of ordered nanoporous ultrathin metal films, but also can be readily extended to the fabrication of other metal-based material films.

10115-44, Session PWed

Grid-type flexible transparent electrode using double-layer structures of gold ribbons and silver nanowires

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We present a unique method to fabricate double-layer structures of gold ribbons and silver nanowires embedded in flexible polymeric substrates. To prepare templates for fabricating the embedded double-layer structures, prism-shaped patterns of n-paraffin (eicosane) was initially prepared on silicon substrate by using micro-contact printing process. Then gold ribbons were deposited on bare Si surface between the prism-shaped patterns of n-paraffin by galvanic displacement reaction. Suspending solution of silver nanowires was drop-casted on gold ribbons. The silver nanowires were selectively deposited on gold ribbons during the evaporation of solvents due to surface energy difference and height contrast of prism-shaped patterns of n-paraffin. After the patterns of n-paraffin were thermally removed, the hierarchical double-layer structures of gold ribbons and silver nanowires only remained on the surface. As poly(dimethyl siloxane) (PDMS) was cured on the samples and peeled off, the double-layer structures were embedded into flexible substrates. Electrical properties of the samples are also characterized by measuring relative change in resistances of the devices under various types of deformations like bending and stretching. In addition, electrochemiluminescent (ECL) device which is driven by alternative current voltage was fabricated by using the double-layer electrode.

10115-45, Session PWed

Block-copolymer-based hierarchical plasmonic nanostructure and its application for molecular detection

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The hierarchical nanostructures have been exploited for various sensors because of their superior sensing ability resulted from the large surface area. Furthermore, those structures made with noble metals show optical signals induced from localized surface plasmon resonance (LSPR), and thus can be used as highly sensitive optical sensors. The detecting light is strongly confined and enhanced in the internal metallic nanostructures so that the small changes of the sensing targets can be captured. To realize hierarchical plasmonic nanostructure with simple and inexpensive fabrication process, we pattern moth-eye nanocone shape into the porous thin film by nanoimprinting. The hierarchical nanocone structure is composed of the nanocones with the size of several hundred nanometers, and the nanopores and branches with the sizes of a few dozen of nanometers inside the nanocones. To make an internal porosity, the nanocone is made of block copolymer which is originally constituted with covalently linked two homopolymer chains and can be selectively etched by a short UV irradiation and chemical etching. After washing and drying, fabricated structure is coated with silver to complete the plasmonic structure. We measured the far-field optical spectrum and Raman intensity to demonstrate the molecular detection capability of our hierarchical plasmonic nanostructure. The enhancement factor of Raman intensity reaches up to ~?10?^6 compared with the signal from the normal molecules.

10115-46, Session PWed

Holographic fabrication of hole arrays in AZO for study of localized surface plasmon resonances

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Transparent conducting oxides are part of a robust material class that is capable of supporting surface plasmon resonances (SPR) in the near-IR which are strongly dependent on size, structure, and doping of the material. This study presents the implementation of holographic lithography to structure large area square lattice cylindrical hole arrays on the transparent conducting oxide thin film, aluminum doped zinc oxide (AZO). For fabricated structures on a glass substrate, SPR are indirectly measured by FTIR transmission spectra and verified with electromagnetic simulations using a finite difference time domain method. Furthermore, it is shown that the SPR excited are standing wave resonances in the (1,1) direction of the lattice array located at the interface of the patterned AZO and glass substrate. This research extends the robust CMOS compatible fabrication techniques of holographic lithography into tunable conductive materials which contributes to the core technology of future integrated photonics.

10115-47, Session PWed

Reliability and manufacturability of 25G VCSELs with oxide aperture formed by in-situ monitoring

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Reliability and manufacturability of 850nm based 25G VCSELs, fabricated at OEpic, are presented. The epitaxial parametric design and the methodology of using a six-inch wafer capable in-situ monitoring and process-controlled oxidation process are critical for high-volume, high-yield, and high-reliability small-aperture sized (5 micron typical), oxide-based VCSELs. This is especially important for 25G 1X4 VCSEL arrays used in 100GBase-SR4 applications. These in-situ oxidation-controlled small aperture 25G VCSELs have demonstrated a Peak Wavelength of 850nm with a Spectral Width (RMS) of 0.4nm, a Threshold Current of <1.0mA, a Slope Efficiency of greater than 0.45W/A, and a Dynamic Resistance (dV/dI) of <70?. Optical Output Power of >5.0mW and Rise/Fall Time of 18/25ps have also been achieved.

Non-hermetically sealed 5 micron and 8 micron aperture sizes of oxide confined VCSELs with active bias of 5mA were stress tested at 125 degree C, for up to 3000 hours. These VCSELs are typically nitride-passivated and stabilization-baked at the wafer level before dicing and carrier mounting for all characterization and reliability testing. Complete reliability, high speed characterization results, and their manufacturability of these 25G VCSELs and VCSEL arrays oxidized with a six-inch in-situ monitored and controlled oxidation process will be presented in the conference.

10115-48, Session PWed

Quantum dot based 3D photonic devices

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Direct fs Laser Writing (DLW) by two-photon polymerization (TPP) is a versatile technique for the creation of solid three-dimensional polymer nanostructures for photonics, biomedical and microfluidic applications. The polymerization process is initiated by a tightly focused ultrafast laser beam due to nonlinear absorption within the focal volume. By employing laser intensities that are only slightly above the nonlinear polymerization threshold, structures with resolution of 100nm can be fabricated.

In this work, we present our most recent results on the fabrication of 3D high-resolution woodpile photonic crystals containing an organic-inorganic silicon-zirconium (Si-Zr) composite and Cadmium Sulfide (CdS) quantum dots (QDs) exhibiting ?(3) nonlinearity and photonic band-gaps at visible wavelengths. The material used in this work is a photo-structurable hybrid silicon-zirconium (Si-Zr) composite synthesized by means of the sol-gel method, where we have incorporated quencher molecules allowing for the fabrication of structures with features sizes well below the diffraction limit, and quantum dot precursors enabling the in situ synthesis of CdS QDs. The incorporation of CdS QDs in the polymer matrix results in a novel CdS-Zr-Si composite material that exhibits a high nonlinear refractive index value measured by means of Z-scan method. Employing DLW and in situ synthesis of CdS QDs, we have successfully fabricated 3D woodpile photonic structures with varying inlayer periodicity from 600nm to 500nm that show clear photonic stop bands in the wavelength region between 1000nm to 450nm measured by means of FTIR spectroscopy.

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10116-1, Session 1

Application of solid tunable lenses in endoscopic systems

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Due to their advances in achieving large focal-length tuning ranges with compact structures, solid tunable lenses based on the Alvarez-Lohmann principle show a promising potential in various applications, especially modern miniature imaging systems. In this paper, we report miniature endoscopic systems integrated with solid tunable lenses for optical adjustable focusing or zooming. The solid tunable lenses are designed according to the improved Alvarez-Lohmann principle, where two independent extended polynomials are employed to govern the two freeform surfaces, respectively. Slim piezo benders aligned along the optical axis are utilized to drive the solid tunable lenses to move laterally. An image fiber bundle is used to transmit the images captured by the optical system to the external cameras. Results show that the endoscopic system is equipped with a capability of optical power tuning from about 135 diopters to about 205 diopters when there is a single solid tunable lens integrated in the system, which enables it to achieve adjustable focus for objects located at different positions. The integration of two solid tunable lenses and two fixed lenses further enables the endoscopic system to have the optical-zooming capability. A zoom ratio of 3x and a maximum full field of view as high as about 80 degrees are realized experimentally. The cross sectional diameter of the endoscopic probe is controlled below 4 mm. The captured images are clear and sharp. Such adjustable-focus or zoom endoscopic systems would be useful in future medical or industrial applications.

10116-2, Session 2

A contribution to the expansion of the applicability of electrostatic forces in micro transducers *(Invited Paper)*

Harald Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany) and Brandenburgische Technische Univ. Cottbus (Germany); Holger Conrad, Matthieu Gaudet, Sebastian Uhlig, Bert Kaiser, Sergiu Langa, Michael Stolz, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Klaus Schimmanz, Fraunhofer-Institut für Photonische Mikrosysteme (Germany) and Brandenburgische Technische Univ. Cottbus (Germany)

Electrostatic forces provide an excellent scaling behavior that makes them first choice for micro and nano actuation. However, large stroke is at cost of large electrode gaps preventing to make use of this advantage. As a consequence, other driving mechanisms like piezoelectricity or electromagnetism are applied, although integration on wafer scale is often more complex and required materials are incompatible to CMOS-processes.

We report on a novel electrostatic actuator class profiting from high forces at electrode separations of a few 100 nm only and providing several 10th of micrometer deflection. The concept is based on transforming the electrostatic forces generated on the surface of a cantilever into a mechanical surface stress resulting in a voltage-dependent curvature of the beam. By suitable designs and fabrication processes a large variety of motion patterns is enabled including bi-directional out-of-plane and in-plane motion as well as membrane deformation. The principle has been investigated by simulation and analytical models and was verified by fabrication and characterization of several types of actuators in SOI technology as well as in surface micromachining technology. The concept provides an extension to state-of-the-art electrostatic actuator technologies. It potentially extends the applicability of electrostatic forces for a large variety of integrated transducers.

10116-3, Session 2

MEMS scanner with 2D tilt, piston, and focus motion

Sebastien Lani, Dara Z. Bayat, Yves Pétremand, Yves-Julien Regamey, Roland Gentsch, Emmanuel Onillon, Jörg Pierer, Julian Kaufmann, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

A MEMS scanner with a high level of motion freedom has been developed. It includes a 2D tilting capability of +/- 15° mechanically, a piston motion of 50µm and a focus/defocus control system of a 2mm diameter mirror. The tilt and piston motion is achieved with electromagnetic actuation (moving magnet) and the focus control with a deformation of the reflective surface with pneumatic actuation. At least one pneumatic channel was fabricated on the compliant membrane and a closed cavity below the mirror surface and connected to an external pressure regulator (vacuum to several bars). The fabrication relies on 3 SOI wafers, 2 for forming the compliant membranes and the integrated channel and 1 to form the deformable mirror. All wafers were then assembled by fusion bonding. Pneumatic actuation for focus control can be achieved from the front or back side; function of packaging concept. A reflective coating can be added to the mirror surface depending on the application. The tilt and piston actuation is achieved by electromagnetic actuation for which a magnet is fixed on the moving part of the MEMS device. Finally, the MEMS device is mounted on a ceramic PCB, containing a micro coil used for actuation. The concept, fabrication, and testing of the devices will be presented.

10116-4, Session 2

Microcontroller based closed-loop control of a 2D quasi-static/resonant microscanner with on-chip piezo-resistive sensor feedback

Richard Schroedter, Markus Schwarzenberg, André Dreyhaupt, Robert Barth, Thilo Sandner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Klaus Janschek, TU Dresden (Germany); Jan Grahmann, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

In this paper we present a 2D raster scanning quasi-static/resonant microscanner being controlled in both axes in closed-loop with on-chip piezo-resistive sensor feedback. While the resonant axis oscillates with a given frequency, the quasi-static axis allows static as well as dynamic deflection up to its eigenfrequency using its staggered vertical comb drive arrangement. Due to the high quality factor of the very low damped spring-mass-system, an adapted trajectory planning using jerk limitation is applied for the quasi-static axis [1]. Nevertheless, inaccuracies of the applied nonlinear micro mirror model and external disturbances lead to undesired residual oscillation in open-loop control mode. To achieve high precision and fast beam positioning, we implement a flatness-based control algorithm with feedback using on-chip piezo-resistive deflection sensors. In comparison to previous work [2,3], we developed a micro controller setup for driving the microscanner, that is equipped with an analog Bessel filter increasing the sensor signal quality significantly. Furthermore, we introduce a digital notch filter to suppress specific frequency components. With a

Fourier analysis of the triangle-shaped command trajectories we estimate the residual error for a desired 2D pattern. In this paper we demonstrate a small size and low power micro mirror driver including high-voltage generation and a microcontroller for real-time control as well as a chip near circuit board for high resolution sensing. We discuss experimental results of open-loop and closed-loop control for different 2D scanning operation. Finally, the intrinsic capability to compensate temperature drifts influencing the piezo-resistive sensor signal is addressed.

10116-5, Session 2

Reliability evaluation of a MEMS scanner

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Previously, the realization and closed loop control of a MEMS scanner integrating position sensors made with piezoresistive sensors was presented. It was consisting of silicon compliant membrane integrating the position sensors on which a mirror and a magnet were assembled. This device was mounted on a PCB containing coils for electromagnetic actuation. In this work, the reliability of such system was evaluated through thermal and mechanical analysis. Thermal analysis has for objective to determine the lifetime of the MEMS scanner and is consisting of temperature cycling (-40°C to 125°C) and accelerated electrical endurance (100°C with power supplied to all electrical components). Mechanical analysis has for objective to determine the resistance of the system to mechanical stress and is consisting of mechanical shock and vibration. A high speed camera has been used to observe the behaviour of the MEMS scanner. The use of shock stopper to improve the mechanical resistance has been evaluated and had demonstrated a resistance increase from 300g to 1300g. The minimum shock resistance required for the system is 500g for transportation and 1000g for portative devices.

10116-6, Session 2

Novel packaging approaches for increased robustness and overall performance of gimbal-less MEMS mirrors

Veljko Milanovic, Abhishek Kasturi, James Yang, Yu Su, Mirrorcle Technologies, Inc. (United States)

2D quasistatic (point-to-point) gimbal-less MEMS mirrors enable arbitrary control of laser beam position and velocity up to their maximum limit. Hence, they provide the ability to track targets, point lasercom beams, and achieve uniform velocity scanning. They are becoming increasingly established in applications including 3D scanning, biomedical imaging, communications, and LiDAR. However, a limitation for their more wide-spread use has been the relatively high susceptibility of large-diameter mirrors to shock and vibrations. Here we study several package-level approaches to increase mechanical damping, shock robustness, and laser power tolerance.

Namely, we study back-filling of MEMS packages with different gases as well as with different (increased) pressures to control damping and in turn increase robustness and useable bandwidth. Additionally, we study the effects of specialized mechanical structures which were fabricated to modify packages to significantly reduce volumes of space around moving structures.

The MEMS mirrors can be modeled as simple spring-mass-damper systems where gas damping dominates the overall structural damping (at ~1atm and higher). In their traditional form and packaging they typically measure a quality factor of 75-100. Increases of pressure result in higher density of gas molecules surrounding the MEMS structures, reducing the overall quality factor to <5. Some gases also exhibit better mirror-cooling properties for high laser power applications (>10W CW). Combination of specialized packaging structures and gas backfill and pressure control provides very efficient heat transfer from the mirror and desired near-critical damping.

The increased performance does not change the compactness and low power consumption - the improved MEMS mirrors still consume <1mW. So far, units (through 3.6mm diameter) with increased damping have passed 500G shock tests.

10116-7, Session 3

Scaling effect and its impact on wavelength-scale microlenses *(Invited Paper)*

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As the scaling effect influences on physical responses of the micro-electro-mechanical systems (MEMS), such a scaling behavior can be found in micro-optical systems, whose responses are quite different from those of macro-sale systems. This is because light interactions strongly depend on the size of optical components with respect to the illuminating wavelength. Since aberrations are related to the optical path difference, they enlarge in proportion to the scaling factor. Thus, the performance of microlenses could be limited by diffraction rather than by aberrations. For small-size lenses, it is easier to achieve the diffraction-limited performance. It means that diffraction will govern the response of such systems.

We start with a discussion of the refraction limit of the miniaturized optical systems using a ball-lens example, and then, move on to link the optical response to the Fresnel number, which is a measure of relative impact of diffraction on the optical systems. Since Fresnel number can be written as a product of the numerical aperture (NA) and the ratio between the element size and the wavelength, constant-NA systems show that the Fresnel number decreases linearly with decreasing the lens size. Eventually, diffraction effect becomes more significant on the optical response, and unconventional phenomena arise, such as, a strong focal shift at relatively high NA lenses. In macroscopic lens systems, such results were never observed. With our study, we shed new light on understanding optical responses of wavelength-scale microlenses, which gain more importance over the last decade.

10116-8, Session 3

Low voltage electrowetting lenticular lens by using multilayer dielectric structure

Junsik Lee, Junoh Kim, Cheoljoong Kim, DooSeub Shin, Gyohyun Koo, Jee Hoon Sim, Yong Hyub Won, KAIST (Korea, Republic of)

Lenticular type multi-view display is one of the most popular ways for implementing three dimensional display. This method has a simple structure and exhibits a high luminance. However, fabricating the lenticular lens is difficult because it requires optically complex calculations. 2D-3D conversion is also impossible due to the fixed shape of the lenticular lens. Electrowetting based liquid lenticular lens has a simple fabrication process compared to the solid lenticular lens and the focal length of the liquid lenticular lens can be changed by applying voltage. 3D and 2D images can be observed with a convex and a flat lens state respectively. Despite these advantages, the electrowetting based liquid lenticular lens demands high driving voltage over several tens of volts with a single dielectric layer structure. A certain degree of thickness of the dielectric layer is essential for a uniform operation and a low degradation over time. This paper presents multilayer dielectric structure which results in low driving voltage. Aluminum oxide deposited by atomic layer deposition (ALD) and parylene C deposited by chemical vapor deposition (CVD) were selected as the multilayer insulators to a thickness such as the single dielectric layer. This method

using the multilayer dielectric structure can achieve a similar quality of the liquid lens when using the single dielectric layer under 10V. We compared the liquid lenticular lens with the multilayer dielectric structure to one with the single dielectric layer in regard to operational characteristics such as the driving voltage and the degradation over time.

10116-9, Session 3

Pitch variable liquid lens array using electrowetting

YooKwang Kim, Jin Su Lee, Junoh Kim, Yong Hyub Won, KAIST (Korea, Republic of)

These days micro lens array is used in various fields such as fiber coupling, laser collimation, imaging & sensor system and beam homogenizer, etc. One of important thing in using micro lens array is, choice of its pitch. Especially imaging systems like integral imaging or light-field camera, pitch of micro lens array defines the system property and thus it could limit the variability of the system.

There are already researches about lens array using liquid, and droplet control by electrowetting. This paper reports the result of combining them, the liquid lens array that could vary its pitch by electrowetting.

Since lens array is a repeated system, realization of a small part of lens array is enough to show its property. The lens array is composed of nine (3 by 3) liquid droplets on flat surface. On substrate, 11 line electrodes are patterned along vertical and horizontal direction respectively. The width of line electrodes is 300um and interval is 500um. Each droplet is positioned to contain three electrode lines for both of vertical and horizontal direction. So there is one remaining electrode line in each of outermost side for both direction. In original state the voltage is applied to only inner (2nd ~10th) electrodes. When voltage of 4th & 8th electrodes are turned off and voltage of outermost (1st & 11th) electrodes are turned on, eight outermost droplets move to outer side, thereby increasing pitch of lens array. The original pitch was 1.5mm and it increased to 2mm after electrodes of voltage applied are changed.

10116-10, Session 3

A fabrication method of opened structures for uniform liquid dosing in liquid lenticular systems

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This study introduces a 3D lenticular system and its fabrication method operating with liquids. The lenses of the lenticular system consists of two immiscible liquids requiring a good uniformity of their amount. The amount is controlled by an opened structures fabricated by silicon KOH etching process. For the fabrication, a low pressure silicon nitride (LSN) is deposited on a bare <1 0 0> silicon wafer followed by a photolithography and a reactive ion etching (RIE) remaining a 200nm LSN layer. A KOH etching process is done for 2 hours with a KOH solution of 40wt% in deionized water. To fabricate the opened structure, a time controlling is required not to be fully etched. The finalized silicon wafer is sputtered by a copper layer as a seed layer for an electroplating. By the electroplating with nickel, a master mold is made. To get the high transparency, poly methyl methacrylate (PMMA) is chosen for the substrate and a hot embossing process is done by fabricated nickel mold with PMMA. The PMMA is coated by gold as a electrode and parylene C and Teflon multi-layer as dielectric layers. For two immiscible liquids, deionized water and a mixture of dodecane and 1-Chloronaphthalene are used. The dosing process is done in underwater environment and the mixed oil is dosed uniformly as the oil has tendency to spread onto the substrate. After sealing the active liquid lenticular devices is fabricated and good uniformity is achieved.

10116-11, Session 3

A miniaturized adaptive-focus camera objective employing a gravity-immune liquid-tunable aspherical lens

Pengpeng Zhao, Caglar Ataman, Hans Zappe, Univ. of Freiburg (Germany)

We have developed a robust method to design liquid-tunable membrane lenses with diffraction-limited tuning of the focal length. Using this method, we designed, fabricated and characterized a tunable aspherical tunable lens with a non-uniform flexible membrane thickness profile, which is also immune to gravity effects. The meniscus shape, which is the defining feature of the device performance, is realized through a precision PDMS casting process using a diamond-turned brass mold with better than 1 μm thickness control. The lens is capable of diffraction-limited performance at its nominal focal length, and has two orders- of-magnitude smaller wavefront error compared to conventional tunable lenses over a large tuning range. The optical performance is unaffected by the lens orientation. The lens has an aperture size of 3 mm, with a nominal focal length of 8 mm and a theoretical diffraction-limited tuning range between 7.2 mm to 8.8 mm. Between 6 mm to 12 mm, the cut-off frequency remains above 50% of the diffraction limit, demonstrating a drastic reduction in spherical aberration compared to conventional liquid-tunable lenses. The gravity-immune behavior is also demonstrated experimentally. To demonstrate the potential of this novel tunable lens, we implemented a focus-tunable camera featuring three fixed lenses and the tunable lens in question. The objective is 5 x 5.5 x 7 mm in dimensions with 40° view angle. By only tuning the aspherical tunable lens within the theoretical diffraction-limited tuning range, the objective can shift its focal plane anywhere between 20 mm and infinity.

10116-12, Session 3

Electrically tunable micro-lens with a strain-enhanced polymer nanocomposite actuator

Florenta A. Costache, Boscij Pawlik, Andreas Rieck, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

A fluid-filled micro-lens concept with an electrically driven polymer actuator was developed in view of optimization of its variation in focal length. The high strain electrostrictive terpolymer P(VDF-TrFE-CFE) was first used in the actuator design for this purpose. Our study showed that the electric field-induced strain in polymer thin films could be even further enhanced by mixing high-k BaTiO3 nanoparticles in the terpolymer.

A newly developed nanocomposite P(VDF-TrFE-CFE) / BaTiO3 ring-shaped actuator was implemented into the 3 mm aperture, liquid-filled micro-lens concept. The micro-lens was fabricated in a wafer-level process flow, which included micromachining of fluidic chambers on silicon wafers, thin film nanocomposite actuator processing, assembly through wafer bonding and chip filling with liquids. Particular characteristics of the nanocomposite were taken into account such as the homogeneous nanoparticle dispersion into the thin film with impact on thin film dielectric breakdown, electrode adherence as well as nanocomposite film etching.

Variable focal length micro-lenses conceps with a single fluidic chamber but also with two fluidic chambers (a design, which can potentially improve the lens membrane stability) were fabricated and characterized. We could demonstrate a wide focal length variation of tens of diopters first for a single chamber plano-convex micro-lens obtained by adjusting the voltage applied on the integrated actuator.

10116-13, Session 4

A fast single-pixel laser imager for VR/AR headset tracking *(Invited Paper)*

Veljko Milanovic, Abhishek Kasturi, James Yang, Mirrorcle Technologies, Inc. (United States)

In this work we demonstrate a highly flexible laser imaging system for 3D sensing applications such as in tracking of VR/AR headsets, hands and gestures. The system uses a MEMS mirror scan module to transmit low power laser pulses over programmable areas within a field of view and uses a single photodiode to measure the reflected light. User can arbitrarily stream the number of pixels to scan over an area and can thus obtain images of target objects at arbitrarily fast rates. The work builds on the previously presented "MEMSEye" laser tracking technology which uses a fast steering MEMS scan module with a modulated laser, and a tuned photosensor to acquire and track a retroreflector-marked object. To track VR/AR headsets, hands and similar objects with multiple markers or no markers at all, a single-point tracking methodology is not sufficient. Cameras could be more appropriate in such multi-point imaging cases but suffer from low frame rates, dependence on ambient lighting, and relatively low resolution. A hybrid method can address the problem by providing a system with its own light source (laser beam), and with full programmability of the pixel locations and scans such that frame rates of 100s of Hz are possible over specific areas of interest. With a modest 1 Mpixel rate of measurement, scanning a sub-region of the field of view with 64 x 64 pixels results in ~200Hz update. Multiple such modules at known locations can be used to scan, and image or track objects with multiple markers and fully obtain their position and attitude in space with sub-5ms updates.

10116-15, Session 4

Electro-optic modulation of high-Q lithium niobate whispering gallery resonator with integrated ground plane

Kenneth Douglas, Sandia National Labs. (United States) and The Univ. of New Mexico (United States); Jeremy Moore, Thomas Friedman, Matthew Eichenfield, Sandia National Labs. (United States)

We experimentally demonstrate electro-optic modulation in thin film lithium niobate microdisk resonators with an integrated bottom electrode fabricated from a z-cut Lithium Niobate on Insulator wafer. The structure consisted of a 400nm thick crystalline z-cut lithium niobate/2um SiO2/20nm Cr/100nm Au/10nm Cr film stack on top of a z-cut lithium niobate handle wafer.

The integrated bottom electrode is located 2um beneath the resonator. This proximity, coupled with positioning an electrical probe close to the top of the resonator, allows large optical frequency shifts with low voltages. We observed a 0.111pm/V resonance shift of vertically polarized (TM) optical whispering gallery modes, with the voltage applied perpendicular to the wafer surface. This corresponds to a shift of one optical linewidth at an applied voltage of 180V, using the r33 component of the eletro-optic tensor. We observed a smaller shift of 0.066pm/V for the radially polarized (TE) modes, using the r13 component of the electro-optic tensor.

The experiment was performed using a 1550nm tunable laser that was coupled to the optical resonator modes using a tapered optical fiber. To measure the electro-optic shift of the resonance, a voltage was applied across the device via DC probe tips and the peak shift was calibrated with a Toptica WS6 IR wavemeter with 200 MHz absolute accuracy. We also present a finite element model that accurately predicts the resonance shift as a function of applied voltage for both polarizations.

10116-16, Session 4

Compact optical MEMS accelerometers and temperature sensors

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Continuous and accurate remote monitoring of acceleration and temperature inside large turbo- and hydro-generators is of crucial importance to prevent extremely expensive system damages and false positives.

Development of optical, metal-free sensors for such systems has gained a lot of attention due to the fact that they are immune to typically very strong electromagnetic fields. Additionally, the sensors made in MEMS technology with differential signal approach guarantee cheap and robust devices and low-noise and linear performance.

Our MEMS temperature sensor is based on measuring a temperature dependent light transmission in silicon. The MEMS accelerometer is based on a seismic MEMS mirror, which in a rest state sends equal amount of light to the output fibres, while in case of the acceleration it redirects more signal to one and less to the other fibre, giving the output differential signal proportional to the acceleration.

Both accelerometer and temperature sensors are made in same Si MEMS technology following a simple process flow, consisting of standard UV photolithography, dry etch and HF release. Prior to microfabrication the devices are optimized using software simulation tools.

Optical setup is used to characterize packaged sensors by measuring their responses to accelerations and temperatures in ranges 0 - 40g and -20°C to +155°C respectively. Highly linear response between set and measured accelerations has been measured. Preliminary tests for temperature sensors also indicate a good linear response.

10116-17, Session 4

Concept for the fast modulation of light in amplitude and phase by an analog tilt-mirror array

Matthias Roth, TU Dresden (Germany); Jörg Heber, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Klaus Janschek, TU Dresden (Germany)

The full complex, spatial modulation of light at high update rates is essential for a variety of applications. In particular, emerging techniques applied to scattering media, such as Digital Optical Phase Conjugation and Wavefront Shaping, request challenging performance parameters. They refer to imaging tasks inside biological media, whose characteristics concerning the transmission and reflection of scattered light may change over time within milliseconds. Thus, these methods call for update rates in the kilohertz range. Existing solutions typically offer limited update rate capabilities, often below 100 Hz, because they rely on liquid crystal (LC) spatial light modulators (SLMs). We propose a diffractive MEMS optical system for this application range. It relies on an analog, tilt-type micro mirror array (MMA) based on established SLM technology. The standard application of this MMA is grayscale amplitude control. We propose a new MMA design allowing high-speed, spatial manipulation of the phase as well.

We study the properties of an appropriate optical setup by simulating the propagation of the light. Our analysis includes several exemplary patterns and a quantitative discussion of the relevant sensitivities to system design parameters.

Our results illustrate the boundaries of the concept with particular focus on the tilt mirror technology. They point towards a promising path to realize the

full complex light modulation at update rates above 1 kHz and resolutions well beyond 10.000 complex pixels. An examination regarding the influence of the polarization concludes the discussion.

10116-18, Session 5

VTT's Fabry-Perot interferometer technologies for hyperspectral imaging and mobile sensing applications *(Invited Paper)*

Anna Rissanen, Bin Guo, Heikki Saari, Antti Näsilä, Rami Mannila, Altti Akujärvi, Harri Ojanen, VTT Technical Research Ctr. of Finland Ltd. (Finland)

(Invited Presentation) VTT's MEMS-based Fabry-Perot interferometers (FPI) technology enables creation of small and cost-efficient microspectrometers and hyperspectral imagers; these robust and light-weight devices are currently finding their way into various novel sensing applications, including emerging medical products, automotive sensors, CubeSat imagers and mobile devices. This presentation gives an overview of our core FPI technologies with recent advances in expanding the field of spectroscopic applications. Spectroscopic analysis is a useful non-contact, selective method for analysing various substances and gases. In recent years, VTT has developed MEMS FPIs and mirrors from UV to thermal IR wavelengths. These technologies have been applied to compact hydrocarbon sensors, thermal infrared gas analysers, and automotive fuel quality sensing as well as a range of novel microspectrometer sensor products. With large optical apertures and high customization capability, FPI technology has also created a basis for various hyperspectral imaging instruments while expanding to novel applications, currently ranging from light-weight CubeSat hyperspectral imagers to unmanned aerial vehicles for precision agriculture, stand-off pollution monitoring as well as for emerging medical instrument products for skin cancer screening. The tunable sensor hardware is typically fully programmable, with volume production capability of MEMS minimizing sensor cost and size - in combination with abundance of image processing power available in mobile devices today and cloud-based spectral data storage, this means that spectroscopic analysis could soon be accessible anywhere. Our recent technology demonstration highlights include a hyperspectral iPhone and a mobile phone CO2 sensor, which aim to advance the field of mobile spectroscopic sensing.

10116-19, Session 5

A miniaturized near infrared spectrometer for non-invasive sensing of bio-markers as a wearable healthcare solution *(Invited Paper)*

Jungmok Bae, Vladislav Druzhin, Alexey Anikanov, Sergey Afanasyev, Alexey Shchekin, Anton S. Medvedev, Alexander V. Morozov, Donho Kim, Sang Kyu Kim, Hyunseok Moon, Hyeongseok Jang, Jonghan Kim, Jaewook Shim, Jongae Park, Samsung Advanced Institute of Technology (Korea, Republic of)

Interest in non-invasive methods of mobile applications grows rapidly in recent decades. Great progress in this field has become possible with development of new compact optical devices allowing analysis of physical and medical-biological parameters of human tissues. In this paper, we report on a miniaturized near infrared spectrometer for non-invasive sensing of bio-markers as a wearable healthcare solution. Main idea of proposed spectrometer is to implement time multiplexing illumination of a skin volume with multiple LED's, each of which having a unique spectral distribution in a spectral region of interest. By sequentially varying of driving parameters of individual LED in an outer rim such as a pulse duration and driving current, a different spectral response from a single cell photodiode at a center, could be then obtained. Based on Tikhonov regularization with singular value decomposition, a spectrum resolution of less than 10nm was obtained first by theoretical computation of reconstruction spectra, based on measured LED spectrum. Such concept was verified with a working prototype covering first overtone band (1500-1800nm) where bio-markers have pronounced absorption peaks and strong water absorption peaks of skin are avoided. The diameter of optical module is 40 mm and thickness is 12 mm, allowing a simple and compact system for wearable applications. To evaluate reconstructed spectrum quality, the measured skin absorption spectra of the prototype was compared with that of a benchtop spectrometer. Cosine metric, a measure of similarity between two non-zero vectors of an inner product space, was measured to be 0.94, showing that the novel concept of miniaturized spectrometer is valid.

10116-20, Session 5

The use of Raman and fluorescence spectroscopy for the discrimination of extra-virgin olive-oil

Naomi McReynolds, Juan M. Auñón Garcia, Zoe Guengerich, Terry K. Smith, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

We present an optical spectroscopic technique, making use of both Raman signals and fluorescence spectroscopy, for the identification of five brands of commercially available extra-virgin olive-oil (EVOO). We demonstrate our technique on both a 'bulk-optics' free-space system and a compact device. Using the compact device, which is capable of recording both Raman and fluorescence signals, we achieved an average sensitivity and specificity of 98.4% and 99.6% for discrimination, respectively. Our approach demonstrates that both Raman and fluorescence spectroscopy can be used for portable discrimination of EVOOs which obviates the need to use centralised laboratories and opens up the prospect of in-field testing. This technique may enable detection of EVOO that has undergone counterfeiting or adulteration. One of the main challenges facing Raman spectroscopy for use in quality control of EVOOs is that the oxidation of EVOO, which naturally occurs due to aging, causes shifts in Raman spectra with time, which implies regular retraining would be necessary. We present a potential method of analysis to minimize the effect that aging has on discrimination efficiency; we show that by discarding the first principal component, which contains information on the variations due to oxidation, we can improve discrimination efficiency thus improving the robustness of our technique.

10116-21, Session 5

Environmental mid-infrared gas sensing using MEMS FTIR spectrometer

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Portable gas sensors with reasonable performance have currently high interest from both the academia and the industry for different commercial applications . Miniaturized MEMS infrared gas sensors are strong candidates for compact and low cost solutions. Most of the gases have their strong fundamental absorption fingerprints in the Mid Infra-Red (MIR) range. However, working in the MIR range is challenging concerning the lower detector performance, availability of components, more light diffraction and so on. In this work we report Carbon Dioxide (CO2) gas sensing in the ambient air in the MIR range around 4250 nm using MEMS Fourier Transform Infra-Red (FTIR) spectrometer. The core engine of the

spectrometer is a scanning Michelson interferometer micro-fabricated using deep etching technology on silicon-on-insulator wafer. Zirconium Fluoride fiber with core diameter 300 μm connects the light source to the interferometer input, and the interferometer output to the Lead Selenide detector. The measured Signal-to-Noise Ratio (SNR) is 24 dB at wavelength 4250 nm and the spectral resolution is 60 cm-1. A free-space detection using Calcium Flouride lenses with light-gas interaction lengths of 12 cm and 120 cm are demonstrated. The experimental results confirm about 400 ppm CO2 concentration detection in the ambient air and the theoretical prediction of the sensitivity limit based on the achieved SNR and resolution is about 15 ppm.

10116-22, Session 6

MOEMS deformable mirror testing in cryo for future optical instrumentation *(Invited Paper)*

Frédéric Zamkotsian, Romain Alata, Patrick Lanzoni, Lab. d'Astrophysique de Marseille (France); Michael A. Helmbrecht, Franck Marchis, Alex Teichman, Iris AO, Inc. (United States)

MOEMS Deformable Mirrors (DM) are key components for next generation optical instruments implementing innovative adaptive optics, phased arrays or beam shaping systems. Due to the wide variety of applications, from astronomy, to microscopy and laser beam shaping, these DMs must perform at room temperature as well as in cryogenic and vacuum environment.

We are testing the PTT 111 DM from Iris AO: this unique and robust design uses an array of single crystalline silicon hexagonal mirrors with a pitch of 606μm, able to move in tip, tilt and piston with strokes from 5 to 7μm, and tilt angle in the range of +/- 5mrad. They exhibit typically an open-loop flat surface figure as good as < 20nm rms.

We are placing this device in our cryo-vacuum chamber designed for reaching 10-5 mbar and < 100K. Our custom Michelson interferometer located in front of the chamber is able to measure performances of the DM at segment as well as whole mirror level, with a lateral resolution of 2μm and a sub-nanometric z-resolution. Segment deformation, mirror shaping, open-loop operation are tested at room and cryo temperature and results are compared. Dynamical response will also be considered. A specific mount including electronic and opto-mechanical interfaces has been designed for fitting in the test chamber. These tests are currently under way.

The goal of this study is to test DMs in cryo and vacuum conditions as well as to improve their architecture for staying efficient in harsh environment.

10116-24, Session 6

Uncooled midwave infrared sensors for spaceborne assessment of fire characteristics

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Spaceborne assessment of fire characteristics relies on radiance measurement of the active fire and contiguous background in a narrow midwave infrared channel. Because the ambient temperature background has low thermal emission in this spectral range, it is difficult to retrieve fire characteristics with the desired accuracy. This paper reports on the details of focal planes of 1017x3 uncooled bolometer pixels specially designed with enhanced midwave infrared absorptance and detectivity to enable more accurate measurements. These focal planes are prepared on space proven monolithic readout electronics that supports simultaneous integration of all pixels for scanning periods of up to 140 ms. Each pixel consists of active, Al shielded, and thermally shorted bolometers arranged in a Wheatstone bridge configuration to reduce the effects of resistive heating and die temperature drift. Bridges with different layout designs of bolometer elements are vacuum sealed in package and characterized under typical in-orbit operating conditions. Under nominal conditions, the selected detectors exhibit a NEP below 70 pW and a response time shorter than 11 ms. Midwave infrared absorptances of up to 0.8 are achieved for the active bolometer elements of these bridges. It is further confirmed that the response of the selected Al shielded bolometer design to high intensity fires is sufficiently low to mitigate the risk of crosstalks between bridge elements. The needs for assessment of fire characteristics over the Canadian territory and the preliminary design of an imaging radiometer system to this end are presented. Using this system to acquire ground pixels in the spectral channel of 3.4-4.2 um from low Earth orbits, NETD of about 3 K and 0.24 K can be achieved respectively for target temperatures of 300 K and 400 K.

10116-25, Session 6

Fabrication of GaAs quantum nanodisk by bio-template, neutral beam etching, asymmetric AlGaAs barrier regrowth and its optical response

Akio Higo, Tohoku Univ. (Japan); Yafeng Chen, Hokkaido Univ. (Japan); Takayuki Kiba, Kitami Institute of Technology (Japan); Cedric Thomas, Institute of Fluid Science, Tohoku Univ. (Japan); Junichi Takayama, Hokkaido Univ. (Japan); Akira Imoto, Soushi Miyazaki, Takeshi Kamikawa, Masahiro Tanaka, KYOCERA Corp. (Japan); Ichiro Yamashita, Nara Institute of Science and Technology (Japan); Yunpeng Wang, Hassanet Sodabanlu, Masakazu Sugiyama, Yoshiaki Nakano, The Univ. of Tokyo (Japan); Akihiro Murayama, Hokkaido Univ. (Japan); Seiji Samukawa, Institute of Fluid Science, Tohoku Univ. (Japan)

Quantum dots (QDs) photonic devices based on III–V compound semiconductor are attractive as an optoelectronic device due to their low power consumption, temperature stability, and high-speed modulation. We have developed a defect-free, top–down fabrication process for 15-nm-diameter GaAs quantum nanodisks (NDs) by employing a biotemplate patterning and neutral beam etching. At first, 12-nm-thick GaAs NDs on 12-nm-thick 17%-Al content AlGaAs barriers nanopillars were fabricated. Then, they were embedded in 30%-Al content AlGaAs asymmetric barrier regrown by metalorganic vapor phase epitaxy (MOVPE). The optical properties were characterized by using the time-resolved photoluminescence spectroscopy. Room temperature operation of GaAs NDs developed by the top-down nanoprocess was performed for the first time with asymmetric barriers. We confirmed that the emission energies of 1.63 eV at 7 K. Transient behavior of the PL as a function of temperature was strongly affected by the quantum confinement effects of the NDs.

10116-26, Session 6

Characteristics of amplitude modulation cantilever sensor with optical waveguide in liquid

Kyung Woon Lee, Korea Univ. (Korea, Republic of); Jinsik Kim, Korea Institute of Science and Technology (Korea, Republic of); Dong-ho Lee, Korea Univ. (Korea, Republic of); Myung-Sic Chae, Kyo Seon Hwang, Korea Institute of Science and Technology (Korea, Republic of); Jung Ho Park, Korea Univ. (Korea, Republic of)

Mechanical transducers such as cantilever and diaphragm need a suitable

media to detect the changes by small particles or bio-molecules in liquid. Especially, the light is suitable media as a reliable detecting method since its high resolution, linear response, reliability, and absence of electrical connections to the cantilever in liquid environments. For that purpose, Silicon oxy-nitride (SiON) based waveguide was fabricated to be imbedded at the cantilever which actuated by piezoelectricity. The cantilever detected target molecules and wave-guided light was modulated by the movement of cantilever with less loss.

Essentially, the basic characteristics of light in SiON waveguide which is imbedded in 2.18 μm thick SiNx/Ta/Pt/PZT/Pt/SiO2 multilayered cantilever should be confirmed to be applicable for liquid phase detection. First of all, the shape and dimension of waveguide to determine the propagation properties were optimized. The total loss including coupling loss was measured and calculated. The optimum position of waveguide at cantilever membrane was also confirmed to reduce the loss by bending of waveguide. For a measurement, laser diode (LD)/photo diode (PD) were used as a source/detector of the light in a visible range. The actuation based on amplitude modulation (AM) is applied for a stable oscillation of the cantilever in liquid environment. Finally, modulated output properties of optical waveguide cantilever were measured and analyzed.

10116-27, Session 6

Observation of thermal fluctuations in a superfluid optomechanical system

Anna Kashkanova, Alexey Shkarin, Charles Brown, Yale Univ. (United States); Lilian Childress, McGill Univ. (Canada); Nathan Flowers-Jacobs, NIST (United States); Scott Hoch, Yale Univ. (United States); Leander Hohmann, Konstantin Ott, Sebastien Garcia, Lab. Kastler Brossel (France) and Ecole Normale Supérieure (France) and PSL Research Univ. (France); Jakob Reichel, Ecole Normale Supérieure (France) and Lab. Kastler Brossel (France) and PSL Research Univ. (France); Jack Harris, Yale Univ. (United States)

In cavity optomechanics the state of a mechanical system can be manipulated by interfacing it with light via radiation pressure. The majority of mechanical systems to date are solid objects (membranes, nanowires, mirrors, etc); however fluids can also be used as a mechanical element. Compared to solids, fluids have an advantage: they don't require careful alignment between the optical cavity and the mechanical element. The fluid can conformally fill or coat the optical cavity.

However almost all optomechanical systems need to be cooled to milliKelvin temperatures in order for quantum effects to be observed. Liquid helium is the only fluid that doesn't solidify under its own pressure at these temperatures. Superfluid helium has negligible optical loss at IR wavelengths, and its acoustic loss is proportional to T^4, which vanishes at low temperatures.

We have developed an optomechanical system in which the mechanical mode is a standing density wave in superfluid helium in a 70 μm long Fabry-Perot cavity. The optical mode is also a mode of the same cavity. Thus, the system is completely self-aligned.

In this system, we drive the mechanical mode with light by modulating the optical intensity. We also observed the mode's undriven Brownian motion and from that extracted the phonon number. We measured phonon number as low as n_m=5. The optomechanical effects of optical spring and optical damping were observed, as were signatures of the mechanical mode's quantum motion. These quantum signatures were the asymmetry and the correlations between the Stokes and anti-Stokes sidebands, which arise from a combination of the mode's zero point motion and the quantum backaction of the optical readout. We found agreement between these measurements and theoretical predictions (to within 20%) over a large range of mode temperatures.

10117-1, Session 1

Configurable and dynamic trapping potentials for ultracold atoms using a DMD device

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The implementation of spatial light modulators (SLMs) in quantum gas experiments has allowed the realization of ever more complex trapping geometries. As ultracold atoms may be sensitive to perturbations of the trapping potential at the 1% level, the high contrast ratios of digital micromirror devices are proving advantageous for use in optical trapping. Our laboratory pursues configurable traps based on the direct (nearly diffraction limited) imaging of a digital micromirror device (DMD).

We achieve highly flexible potentials using commercially available microscope objectives external to our vacuum chamber that directly project the DMD to the atom plane, producing optical traps over an area of 130 ?m ? 200 ?m, with a resolution of 630(10) nm full width at half maximum (FWHM) at 532 nm illumination. We combine these potentials with a horizontally propagating TEM00 or TEM01 Hermite-Gaussian optical sheet that provides vertical confinement. With the dynamic control enabled by the maximum full-frame rate of 20 KHz and on-board storage of >13,000 frames of the DMD, we study the transport of atoms and superfluid dynamics in configurable trapping geometries. Using the fast frame rate of the DMD we also produce intermediate grey levels that complement half-toning techniques for producing optimized grayscale patterns.

10117-2, Session 1

Micro mirrors based efficient coupling of light to multi core fiber realizing in-fiber photonic neural network processor

Eyal Cohen, Dror Malka, Amir Shemer, Asaf Shahmoon, Bar-Ilan Univ. (Israel); Michael London, The Edmond and Lily Safra Ctr. for Brain Sciences, The Hebrew Univ. of Jerusalem (Israel); Zeev Zalevsky, Bar-Ilan Univ. (Israel)

Hardware implementation of artificial neural networks facilitates real-time parallel processing of massive data sets. Optical neural networks offer low-volume 3D connectivity together with large bandwidth and minimal heat production in contrast to electronic implementation. Here, we present a conceptual design for in-fiber optical neural networks. Neurons and synapses are realized as individual silica cores in a multi-core fiber. Optical signals are transferred transversely between cores by means of optical coupling. Pump driven amplification in erbium-doped cores mimics synaptic interactions. In order to dynamically and efficiently couple light into the multi core fiber a micro mirrors based (DMD) based micro mirror device is used to perform proper beam shaping operation. The beam shaping reshapes the light into a set of points in space matching the positions of the required cores in the entrance plane to the multi core fiber.

10117-3, Session 1

Ultrafast femtosecond laser beam shaping and axial scanning using a digital micromirror device

Jiyi Cheng, Qiang Geng, Shih-Chi Chen, The Chinese Univ. of Hong Kong (Hong Kong, China)

We will present the design and application of the first digital micromirror device (DMD)-based ultrafast beam shaper (DUBS) for arbitrarily modulating the phase and amplitude of femtosecond lasers at the DMD pattern rate, i.e., 4.2 – 32.5 kHz. In the DUBS, the spectrum of the input pulsed laser is first angularly dispersed by a transmission grating and subsequently imaged to a DMD with beam modulation patterns; the transmission grating and a high-reflectivity mirror together compensate the angular dispersion introduced by the DMD. To demonstrate the utility of ultrafast beam shaping, we integrate the DUBS with a custom-built video-rate two-photon microscope to perform ultrafast axial scanning, which may be realized by programming binary holograms of spherical wavefronts of increasing/decreasing radii to the DMD. We have derived the parametric relationships between the DMD parameters, i.e., aperture and pixel size, and the axial scanning characteristics, including (1) maximum optical power, (2) minimum step size, and (3) scan range. In the preliminary experiments, we scanned a pollen sample via both the DMD-scanner and a precision z-stage. The results show the DMD scanner generates images of equal quality throughout the scanning range. The overall efficiency of the TPE system was measured to be ~3%. With the high scanning rate, the DMD-scanner may find important applications in random-access imaging or high-speed volumetric imaging that enables visualization of highly dynamic biological processes in 3-D with sub-millisecond temporal resolution.

10117-4, Session 2

Reaction of photochemical resists used in screen printing under the influence of digitally modulated ultra violet light

Tommy Gmuender, Sign-Tronic AG (Switzerland)

Different chemical photo-reactive emulsions are used in screen printing for stencil production. Depending on the bandwidth, optical power and depth of field from the optical system, the reaction / exposure speed has a diverse value. In this paper the emulsions get categorized and validated in a first step. After that a mathematical model gets developed and adapted due to heuristic experience to estimate the exposure speed under the influence of digitally modulated ultra violet light.

The main intention is to use the technical specifications (intended wavelength, exposure time, distance to the stencil, electrical power, stencil configuration) in the emulsion datasheet primary written down with an uncertainty factor for the end user operating with large projector arc lamps and photo films. These 5 parameters are the inputs for a mathematical formula which gives as an output the exposure speed for the computer to screen (CTS) machine calculated for each emulsion / stencil set-up.

The importance of this work relies in the possibility to rate with just a few boundaries the performance and capacity of an exposure system used in screen printing instead of processing a long test series for each emulsion / stencil configuration. This approach is adaptable for the requirements found in Computer to Plate (CTP) and Computer Lithography (CL). Surplus from this work under the scientific point of view is that no known producer of CTS machines (according to the current state of knowledge) is using this approach to determine the exposure speed of the optical projector system.

10117-5, Session 2

Digital micromirror device based adaptive optics approach for enhanced micro-machining fidelity

Daniel J. Heath, Ben Mills, James A. Grant-Jacob, Matthias Feinaeugle, Vitali Goriainov, Richard Oreffo, Robert W. Eason, Univ. of Southampton (United Kingdom)

Digital micromirror devices (DMDs) have found many scientific research applications. We present adaptive optics techniques exploiting the point spread function (PSF) of a DMD pixel to enhance the fidelity of image-projection-based laser machining. Femtosecond laser pulses with intensity profiles spatially shaped by a DMD were demagnified to a sample via a microscope objective, with ~10 DMD mirrors, each of width ~10μm, approximately projecting to the optical setup diffraction limit of ~1μm. A single DMD mirror then scales geometrically to dimensions well below the diffraction limit, permitting various techniques to enhance machining. By digitally shifting an intensity mask on the DMD between pulses while the sample remains static, machined features with resolutions below the single-exposure diffraction limit are produced (similar to pitch splitting multiple exposure techniques), with a reduction of >2.5x achieved in nickel. By combining digital image shifts with real-time sample image recognition algorithms, point-to-point positional accuracy is camera-resolution-limited (~500nm) rather than translation stage-limited. Furthermore, the PSF allows near-continuous intensity distributions rather than binary on/off intensity patterns, and have been used to produce variable-depth surface texturing (up to 40nm depth changes with 2μm period demonstrated in metals) features via single shots. Algorithms have been used to automate optical proximity corrections for arbitrary intensity masks in order to reduce machining errors due to optical filtering. These techniques are being combined to produce >1cm2 size, highly complex substrates for the production of biologically-friendly cell growth assays, with the viability of human bone stem cells on flexible substrates demonstrated.

10117-7, Session 3

High-speed 3D imaging using digital binary defocusing method vs sinusoidal method *(Invited Paper)*

Song Zhang, Beiwen Li, Purdue Univ. (United States)

In recent decades, the structured light technology has been transported into microscopic level by a variety of means with different hardware setups, yet not enough research works have been reported to examine the effects of different projection patterns. Conventionally, 8-bit sinusoidal patterns are used for pattern projection, which suffers from speed bottleneck and requires gamma correction. In contrast, the binary defocusing technique approximates sinusoidal projection by defocusing 1-bit binary pattern. With the advanced digital-light-processing (DLP) projection technology, it can reach unprecedented high-speed (i.e. kiloHertz) 3D sensing rate without requiring gamma correction. Since the binary pattern produces the highest possible contrast, we hypothesize that the binary defocusing technique can also increase the signal-to-noise ratio (SNR) and thus the measurement accuracy. In this research, we compare the binary defocusing technique with conventional sinusoidal method under two different types of microscopic 3D profilometry systems: 1) both camera and projector use telecentric lenses; 2) only camera uses a telecentric lens. We will present simulation and experimental results showing that binary defocusing technique can improve depth measurement resolution of conventional sinusoidal method up to 19%. Moreover, by taking the speed advantage of the binary defocusing technique with a DLP projector, we will also present a high-speed (500 Hz) and high-resolution (1600 ? 1200) 3D microscopic profilometry system that could reach kHz at a reduced resolution.

10117-8, Session 3

Advanced optical 3D scanners using DMD technology *(Invited Paper)*

Peter Muenstermann, AICON 3D Systems GmbH (Germany)

Optical 3D measurement techniques are state-of-the-art for highly precise, non-contact surface scanners - not only in industrial development, but also in near-production and even in-line configurations. The need for automated systems with very high accuracy and clear implementation of national precision standards is growing extremely due to expanding international quality guidelines, increasing production transparency and new concepts related to the demands of the fourth industrial revolution. The presentation gives an overview about the present technical concepts for optical 3D scanners and their benefit for customers and various different applications – not only in quality control, but also in design centers or in medical applications. The advantages of DMD-based systems will be discussed and compared to other approaches. Looking at today's 3D scanner market, there are a confusing amount of solutions varying from low-price solutions to high end systems. Many of them are linked to a very special target group or to special applications. We will clarify the differences of the approaches and will discuss some key features which are necessary to get optical measurement systems suitable for industrial environments. The paper will be completed by examples for DMD-based systems, e. g. RGB true-color systems with very high accuracy like the StereoScan neo of AICON 3D Systems. Typical applications are shown and the benefits for customers using such systems are described.

10117-9, Session 3

Calibration for 3D Imaging with a Single-Pixel Camera

Jeremy Gribben, Ajile Light Industries Inc. (Canada) and Univ. of Ottawa (Canada); Alan R. Boate, Ajile Light Industries Inc. (Canada); Azzedine Boukerche, Univ. of Ottawa (Canada)

Structured light 3D imaging systems are traditionally calibrated by first calibrating the camera, then using the camera results to calibrate the projector. This leads to two sources of error: any camera calibration errors are cumulative with the projector calibration, and detecting the projected calibration patterns on top of the physical calibration artefact is error prone. By enabling our projector to both project images as well as capture them using the same optical path, our approach is to measure the physical calibration artefact directly with the projector and perform its calibration independently of the camera. This is achieved by replacing one of the LEDs in our DMD based projector with a photodetector, effectively turning our projector into a dual-purpose device which uses the same optical path to both project and capture images as a single-pixel camera (SPC). Here, coded apertures using the full Hadamard sequence were displayed on the DMD and sampled by the photodetector ADC circuit. A scanning method was developed to first coarsely capture an image of the calibration artefact with the SPC to locate target points. Then using a set of higher resolution regions of interest centred on these points we obtain subpixel accuracy. After calibration, the same SPC system is used to project structured light patterns which are captured by our CMOS camera to generate 3D images. Our new SPC based approach leads to improved depth measurement accuracy in 3D imaging by providing an internally consistent calibration method which reduces cumulative errors caused by multiple imaging paths.

10117-10, Session 3

Fiber-optic fringe projection with crosstalk reduction by adaptive pattern masking

Steffen Matthias, Markus Kästner, Eduard Reithmeier, Leibniz Univ. Hannover (Germany)

To enable in-process inspection of industrial manufacturing processes, measuring devices need to fulfil time and space constraints, while also being robust to environmental conditions, such as high temperatures and electromagnetic fields. A new fringe projection profilometry system is being developed, which is capable of performing the inspection of filigree tool geometries, e.g. gearing elements with tip radii of 0.2 mm, inside forming machines of the sheet-bulk metal forming process. Compact gradient-index rod lenses with a diameter of 2 mm allow for a compact design of the sensor head, which is connected to a base unit via flexible high-resolution image fibers with a diameter of 1.7 mm. The base unit houses a flexible DMD based LED projector optimized for fiber coupling and a CMOS camera sensor. The system is capable of capturing up to 150 grayscale patterns per second as well as high dynamic range images from multiple exposures. Due to fiber crosstalk and light leakage in the image fiber, signal quality suffers especially when capturing 3 D data of technical surfaces with highly varying reflectivity or surface angles. An algorithm is presented, which adaptively masks parts of the pattern to reduce these effects via multiple exposures. The masks for valid surface areas are automatically defined according to different parameters from an initial capture, such as intensity and surface gradient. In a second step, the masks are re-projected to projector coordinates using the mathematical model of the system. This approach reduces both inter-pixel crosstalk and double reflections on concave objects while maintaining measurement durations of less than 3 s.

10117-11, Session 4

Light-induced quantitative microprinting of biomolecules

Pierre-Olivier Strale, Ammar Azioune, Ghislain Bugnicourt, Yohan Lecomte, Makhlad Chahid, Vincent Studer, Interdisciplinary Institute for NeuroScience (France) and Univ. Bordeaux Segalen (France) and Ctr. National de la Recherche Scientifique (France)

Printing of biomolecules on substrates has developed tremendously in the past few years. The existing methods either rely on slow serial writing processes or on parallelized photolithographic techniques where cumbersome mask alignment procedures usually impair the ability to generate multi-protein patterns. We recently developed a new technology allowing for high resolution multi protein micro-patterning. This technology named "Light-Induced Molecular Adsorption of Proteins (LIMAP)" is based on a water-soluble photo-initiator able to reverse the antifouling property of polymer brushes when exposed to UV light.

Our optical set-up is composed of a wide-field DMD based projection system coupled to a conventional microscope and permits to generate arbitrary grayscale patterns of UV light at the micron scale. Interestingly, the density of adsorbed molecules scales with the dose of UV light thus allowing the patterning of gradients. The very low non specific background of biomolecules outside of the UV-exposed areas allows for the sequential printing of multiple proteins without alignment procedures. Protein patterns ranging from 500 nm up to 1 mm can be performed within seconds, as well as gradients of arbitrary shapes.

The range of applications of the LIMAP approach extends from the single molecule up to the multicellular scale with an exquisite control over local protein density. We show that it can be used to quantitatively study biomolecular interactions at the single molecule level but also to generate complex and dynamic protein landscapes useful for cell-cell and cell-matrix interactions studies.

Moreover, the DMD-based spatial control of light can be combined with functionalized UV-sensitive hydrogels precursors opening new doors to highly controlled 3D cell cultures.

10117-12, Session 4

Multiplexed illumination for optical diffraction tomography using a digital micromirror device

Di Jin, Renjie Zhou, Zahid Yaqoob, Peter T. C. So, Massachusetts Institute of Technology (United States)

Optical diffraction tomography (ODT), using an interferometric microscopy technique, can quantitatively measure the three-dimensional (3-D) refractive index (RI) distribution in transparent samples. ODT features unique advantages such as non-invasive, label-free, and high-resolution imaging; these capabilities have been increasingly explored recently, particularly in the field of cell biology. Normally, the RI map is reconstructed by solving the inverse scattering problem using more than one hundred holograms, which correspond to various angles of illumination. Current reconstruction methods all require that each hologram is created by only one illumination angle. Therefore, the number of measurements must be equal to the number of needed illumination angles, thus limiting ODT for video-rate or real-time imaging applications. To overcome this issue, we propose a new ODT system together with a new reconstruction algorithm. In the proposed optical system, the illumination is multiplexed by coding a digital micromirror device to display a series of Lee holograms, each of which corresponds to a plane wave of a specific incident angle in the sample plane. On the other hand, the reconstruction algorithm uses the beam propagation method to model the sample scattering process, as well as the error propagation method to train the artificial neural network which represents the RI distribution of the sample. This novel method is expected to reduce the measurement time by a factor of 4-6, which is crucial for video rate or even real time tomography imaging applications such as label-free 3-D imaging cytometry.

10117-13, Session 4

Intraoperative NIR tomography system based on spatially modulated illumination using the DLP4500 evaluation module

Sang Hoon Chong, Ashwin B. Parthasarathy, Venkaiah C. Kavuri, Univ. of Pennsylvania (United States); Frank A. Moscatelli, Swarthmore College (United States); Sunil Singhal, Hospital of the Univ. of Pennsylvania (United States); Arjun G. Yodh, Univ. of Pennsylvania (United States)

We present a biomedical application of Digital Micro-mirror technologies by adapting the DLP4500 module for quasi real-time intraoperative tumor imaging. Fluorescence image guided surgery has been increasingly popular due to its ability to inform surgeons about tumor boundaries in real-time. We have extended this technique to provide 3D tomographic images of a tumor, by adapting a DLP4500 device to illuminate the surgical field with spatially modulated near-infrared (NIR) light. We combine the digital micro-mirror device (DMD) with two simultaneously triggered CMOS cameras to realize a spatial frequency domain imaging system. Spatial frequency domain imaging utilizes sinusoidally modulated illumination at different spatial frequencies and three different phases; corresponding signals are readily demodulated, and analyzed to derive a 3D fluorescence image. Our DMD device is commercially modified and equipped with high-power (5W) NIR diode laser. We present a brief discussion of data acquisition using DLP4500 module, and corrections for spatial inhomogeneity and gamma adjust in order to create linear/desired sinusoidal illumination of NIR light. We discuss results from a tissue phantom study and in-vivo experiments.

10117-15, Session 4

Improvement of axial excitation confinement in temporal focusing-based multiphoton microscopy via spatially modulated illumination

Chia-Yuan Chang, Shean-Jen Chen, National Cheng Kung Univ. (Taiwan)

Two photon excitation fluorescence (TPEF) uses near-infrared wavelength in the low absorption spectral window is a powerful tool for generating fluorescence signal deep inside biological specimen within micron/submicron resolution. Temporal focusing-based multiphoton excitation microscopy (TFMPEM) provides widefield TPEF imaging directly. The diffraction element in TFMPM separates different spectral components of ultrashort laser pulse into different angles induces spatial dispersion that broadens laser pulse width. In the 4-f system setup, the diverse spectral components would temporally overlap in phase only at the focal plane of the objective lens to reconstruct the shortest pulse width that is sufficient to excite the TPEF signal. The TFMPM could apply for fast Brownian motion tracking, widefield fluorescence lifetime imaging, and 3D neuronal activity observation. a developed TFMPEM with a single DMD that works as the blazed grating for light spatial dispersion and simultaneously provides patterned illumination has been extended to implement spatially modulated illumination in structured frequency and orientation. The spatially modulated illumination via the DMD could be designed to force the beam shape with better uniformity and larger area coverage at the back aperture of objective according to overall distributions of spatial dispersion and pattern diffraction. With a multi-orientation and saturated sinusoidal pattern, the axial excitation profile could achieve 1.5 ?m which is almost 2-fold enhancement. With the better contrast of pattern illumination, the better performance of the image reconstruction results would be expected. Therefore, using the HiLo microscopy with condensed AEC is obviously superior in contrast and scattering distortion in the biotissue images.

10117-25, Session 4

Controlled power delivery for super-resolution imaging of biological samples using digital micromirror device

Liyana Valiya Peedikakkal, Ashley J. Cadby, The Univ. of Sheffield (United Kingdom)

Optical microscopy has played a significant role in biological research due to its non-contact, minimal invasive nature enabling in vivo investigation. The well-known Abbe diffraction limit has initiated the development of super resolution optical microscopy which opens tremendous scope for the study of biological samples. Super resolution images of a sample is generally achieved by using high power laser illumination with long exposure time which unfortunately increases photo-toxicity of a sample, making super resolution microcopy, in general, incompatible with live cell imaging.

Furthermore, the limitation of photobleaching reduces the ability to acquire time lapse images of live biological cells using fluorescence microscopy. Digital Light Processing (DLP) technology can put down light at grey scale levels by flickering digital mirco-mirrors at around 290 Hz enabling highly controlled power delivery to samples.

In this work, Digital Micro-mirror Device (DMD) is implemented in an inverse Schiefspiegler telescope setup to control the power and pattern of illumination for super resolution microscopy. We can achieve spatial and temporal patterning of illumination by controlling DMD pixel by pixel. The DMD allows us to control the power and spatial extent of the laser illumination. This allows us to, in real time, change between a number of imaging modalities such as confocal microscopy, Structured Illumination Microscopy (SIM), Stochastic Optical Reconstruction Microscopy (STORM) and as such trade photo-toxicity for resolution. We have used this to show that we can reduce the power delivered to the sample to allow for long term imaging in one area while achieving sub-diffraction imaging in another using higher power densities.

10117-16, Session 5

Compressive Sensing for Single-Shot Two-Dimensional Coherent Spectroscopy *(Invited Paper)*

Elad Harel, Austin Spencer, Boris Spokoyny, Northwestern Univ. (United States)

Compressive sensing (CS) is a general framework by which signals may be efficiently captured by exploiting their sparsity in a suitable domain. Here, we demonstrate experimental implementation of sparse spatial sampling to capture the electronic structure and ultrafast dynamics of molecular systems using phase-resolved two-dimensional coherent spectroscopy. Until now, nonlinear spectroscopy has been hampered by its reliance on array detectors that operate in limited regions of the electromagnetic spectrum. The method described, which we call Single Point Array Reconstruction by Spatial Encoding (SPARSE) Spectroscopy, completely eliminates the need for array detectors while increasing the acquisition speeds by orders of magnitude compared to scanning methods. Combining spatiotemporal encoding of the nonlinear optical response and signal modulation by a high-speed digital micromirror, allows us to retrieve quantum state-resolved correlation maps in a complex dye molecule and photosynthetic protein. We report mathematically complete Hadamard reconstruction and compression factors as high as 10 using compressive sensing, both in good agreement with directly detected spectra. We envision unprecedented possibilities for coherent spectroscopy using broadband light sources, including frequency comb and super-continua, in so-far unexplored regions of the electromagnetic spectrum.

10117-17, Session 5

Side information in coded aperture compressive spectral imaging *(Invited Paper)*

Laura V. Galvis Carreno, Univ. of Delaware (United States); Henry Arguello Fuentes, Univ. Industrial de Santander (Colombia); Daniel L. Lau, Univ. of Kentucky (United States); Gonzalo R. Arce, Univ. of Delaware (United States)

Coded aperture compressive spectral imagers sense a three-dimensional cube by using two-dimensional projections of the coded and spectrally dispersed source. These imagers systems often rely on FPA detectors, SLMs, micromirror devices (DMDs), and dispersive elements. The use of the DMDs to implement the coded apertures facilitates the capture of multiple projections, each admitting a different coded aperture pattern. The DMD allows not only to collect the sufficient number of measurements for spectrally rich scenes or very detailed spatial scenes but to design the spatial structure of the coded apertures to maximize the information content on the compressive measurements. Although sparsity is the only signal characteristic usually assumed for reconstruction in compressing sensing, other forms of prior information such as side information have been included as a way to improve the quality of the reconstructions. This paper presents the coded aperture design in a compressive spectral imager with side information in the form of RGB images of the scene. The use of RGB images as side information of the compressive sensing architecture has two main advantages: the RGB is not only used to improve the reconstruction quality but to optimally design the coded apertures for the sensing process. The coded aperture design is based on the RGB scene and thus the coded aperture structure exploits key features such as scene edges. Real reconstructions of noisy compressed measurements demonstrate the benefit of the designed coded apertures in addition to the improvement in the reconstruction quality obtained by the use of side information.

10117-18, Session 5

Region of interest hyperspectral imaging

Martin Theuring, Bartlomiej Grychtol, Fraunhofer-Institut für Produktionstechnik und Automatisierung (Germany); Nikolas Dimitriadis, Fraunhofer-Institut für Produktionstechnik und Automatisierung (Germany) and Ruprecht-Karls-Univ. Heidelberg (Germany); Nikolaos C. Deliolanis, Fraunhofer-Institut für Produktionstechnik und Automatisierung (Germany)

Hyperspectral imaging allows the examination of an object throughout a broad spectral range. However, data acquisition is usually accompanied by a trade-off between spatial and spectral resolution. This restriction especially applies for monitoring time-variant processes or sceneries. Additionally, when combining high spectral with high spatial resolution, the amount of data, which is generated during the measurement process, requires large data storage capacities and powerful computers for prompt analysis and decision making.

In many applications, it is sufficient to collect spectral information only from specific regions of interest that have uniform optical properties. The approach would ease data storage and significantly facilitate data analysis and visualization. However, for these use cases, dedicated measurement instrumentation is currently not available.

In this work, we present a novel technology platform which combines regular color imaging with the continuous spectral analysis of a user defined region of interest. A digital micromirror device (DMD) is used to select specific regions of interest from which to collect the light and hence to obtain the spectral information. In order to accommodate for temporal changes in the object plane (for instance a displacement of the region of interest), image processing and object tracking algorithms are applied to readjust the DMD accordingly. The platform is laid out such that it can be adopted to various optical imaging systems (e. g. endoscope, microscope). The technology is demonstrated in a test environment using a custom software for real-time hardware control and data visualization.

10117-19, Session 5

Conceptual design for an AIUC multi-purpose spectrograph camera using DMD technology

Surangkhana Rukdee, Franz E. Bauer, Holger Drass, Leonardo Vanzi, Andres Jordan, Filipe Barrientos, Pontificia Univ. Católica de Chile (Chile)

Current and upcoming massive astronomical surveys discover a torrent of objects, which need ground-based follow-up observations to characterize their nature. For transient objects in particular, rapid early spectroscopic identification is needed. We design a Digital Micromirror Device (DMD) multi-purpose spectrograph camera capable of running in several modes: traditional longslit mode, small-field patrol IFU mode, multi-object mode and IFU mode via Hadamard spectra reconstruction. We place a commercial DMD at the telescope focal plane to allow different input modes for the spectrograph. AIUCOCAM is a low resolution spectrograph of R~1,600 covers the spectral range of 0.45-0.85 μm. We employ a VPH grating as a disperser, which is removable for an imaging mode. The design minimizes the number of surfaces in the spectrograph to target a 40% throughput. Preliminary results indicate image quality of 1.5" PSF. This spectrograph is envisioned for use on a 1-2m class telescope in Chile (e.g., 2.5m duPont telescope), to take advantage of good site conditions. We present a design decisions and challenges of a cost-effective robotized spectrograph.

10117-20, Session 5

A method of incident angle estimation for high resolution spectral recovery in filter-array-based spectrometers

Cheolsun Kim, Woong-Bi Lee, Gun Wu Ju, Gwangju Institute of Science and Technology (Korea, Republic of); JeongHoon Cho, Seongmin Kim, Jinkyung Oh, Dongsung Lim, P-Cube Co., Ltd. (Korea, Republic of); Yong Tak Lee, Heung-No Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

In recent years, there has been an increasing interest in miniature spectrometers for research and development. Miniature spectrometers have advantages of cost and size, and they can be applied in various fields such as pharmacy, forensic and quality control. As a kind of spectrometers, optical filter-array-based spectrometers have a great potential to be minimized since the filter-array can be placed directly onto detector-array. However, miniaturization causes a lot of degradation of spectral resolution. Nowadays, a number of studies have been reported that the filter-array-based spectrometers equipped with digital signal processing (DSP) have achieved a high resolution in spectral recovery. The performance of the spectral recovery using the DSPs highly depends on the prior information of transmission functions (TFs) of the filters. The TFs vary with respect to the incident angle onto the filter-array. In previous studies, the incident angle was assumed to be known and fixed as a normal incidence. In practice, however, the incident angle is inconstant and unstable according to unpredictable environments and applications. This problem yields an important issue for applying DSP to the filter-based spectrometers. In this paper, we propose a method of incident angle estimation for high resolution spectral recovery in the filter-array-based spectrometers. By exploiting sparse signal reconstruction of the l1 norm minimization, the DSP technique determines a set of TFs among all possible sets of TFs, which maximize the energy of the reconstructed signal. Based on the incident angle estimation, the DSP for high resolution spectral recovery is effective on the performance of the filter-array-based spectrometers.

10117-21, Session 6

The CAOS camera platform: Ushering in a paradigm change in extreme dynamic range imager design *(Invited Paper)*

Nabeel A. Riza, Univ. College Cork (Ireland)

Multi-pixel imaging devices such as CCD, CMOS and FPA photo-sensors dominate the imaging world. These Photo-Detector Array (PDA) devices certainly have their merits including increasingly high pixel counts and shrinking pixel sizes, nevertheless, they are also being hampered by limitations in instantaneous dynamic range, inter-pixel crosstalk, quantum full well capacity, signal-to-noise ratio, sensitivity, spectral flexibility, and in some cases, imager response time. Recently invented is the Coded Access Optical Sensor (CAOS) Camera platform that works in unison with current Photo-Detector Array (PDA) technology to counter fundamental limitations of PDA-based imagers while providing high enough imaging spatial resolution and pixel counts. Using for example the Texas Instruments (TI) Digital Micromirror Device (DMD) to engineer the CAOS camera platform, ushered in is a paradigm change in advanced imager design, particularly for extreme dynamic range applications.

10117-22, Session 6

Full-color stereoscopic single-pixel camera and disparity map generation using DMD technology

Eva Salvador-Balaguer, Pere J. Clemente Pesudo, Enrique Tajahuerce, Filiberto Pla, Jesús Lancis, Univ. Jaume I (Spain)

Imaging systems based on microstructured illumination and single-pixel detection offer several advantages over conventional imaging techniques. They are an effective method to image objects through scattering media even in the dynamic case. They work efficiently under low light levels, and the simplicity of the detector makes it easy to design imaging systems working out of the visible spectrum and to acquire multidimensional information. In particular, several approaches have been proposed to record 3D information. The technique is based on sampling the object with a sequence of microstructured light patterns codified onto a programmable spatial light modulator while light intensity is measured with a single-pixel detector. The image is retrieved computationally from the photocurrent fluctuations provided by the detector.

In this contribution we propose an optical system able to produce full-color stereoscopic images by using few and simple optoelectronic components. In our setup we use an off-the-shelf digital light projector (DLP) based on a digital micromirror device (DMD) to generate the light patterns. To capture the color of the scene we take advantage of the codification procedure used by the DLP for color video projection. To record stereoscopic views we use a 90º beam splitter and two mirrors, allowing us two project the patterns form two different viewpoints. By using a single monochromatic photodiode we obtain a pair of color images that can be used as input in a 3-D display. To reduce the time we need to project the patterns we use a compressive sampling algorithm. Experimental results are shown.

10117-23, Session 6

A novel emissive projection display (EPD) on transparent phosphor screen

Ted Sun, Ge Yu, Botao Cheng, SuperImaging Inc. (United States); Leonard Sun, SuperImage Technologies Inc (United States)

In this presentation, the latest development on the transparent EPD system will be described, including the characters of the display screens and the matching “excitation” projectors. EPD enables the following new projection displays that can not be properly served with existing digital displays:

1. High Quality Emissive Display on Water-Clear Phosphor Screen, which can be readily applied onto any glass window or windshield. For example, an entire windshield can be converted to a fully transparent heads-up display (HUD) with unlimited field of view; Glass window or panel can be converted to an optic clear emissive digital signage with unlimited viewing angles.

2. High contrast projection onto pitch-black emissive screen. Conventional diffusive or reflective projection screen presents inferior image contrast, black level, and color properties in lighted environment compared to emissive display such as plasma or OLED. By applying the transparent emissive coating onto a black screen or substrate and project “excitation” image, it present a high quality emissive image onto the black background, resulting a image quality that rivals emissive displays on scalable, economic, and portable projection screen.

10117-24, Session 6

Optical emulator of quantum computing using CW Laser, DMD and LCD spatial modulator

Luigi Loreti, L.B.Opto s.r.l. (Italy)

In this paper we present a Quantum Computer Emulator (up to 16 qubits) using polarized coherent laser light as qubit, LCD as phase light modulator and two DMD, one for addressable qubit register and the other for Intensity light modulator. It can optically perform all the elementary quantum gates (X, H, C-NOT. Toffoli , SWAP and total light phase rotation) using up to 65000 parallel light beams (16 qubits).

Each light beam represents one of the all possible superposition states of the incoming 16 qbits data. All the beams, in parallel, can be modulated in phase with an LCD SLM, in amplitude, position and swap with the 2 DMD and measured with a CMOS CCD camera. A GUI software is used to draw, edit and transfer quantum circuits to the emulator.

10118-2, Session 1

Fluorescent diamond probes: charge sensing and intracellular delivery *(Invited Paper)*

Milos Nesladek, Univ. Hasselt (Belgium)

The talk discusses recent technological progress in fabrication of NV fluorescent nanodiamond probes for intracellular sensing. Highly luminescent nanodiamond can be fabricated, by electron or proton irradiation. This includes irradiation using liquid targets yielding high homogeneity in concentration of NV centers over the irradiation batch. The surface functionalization methods, including selective substitution of surface groups by fluorine, stabilize NV- luminescence and provide probes, sensitive to NV0 - NV- charge switching. The charge sensing, using NV0 - NV conversion is further explained and used as sensitive method for detection of charge molecules and used for real time monitoring of DNA delivery. Finally prospects for using NV diamond probes, including particles with size < 10 nm for intracellular sensing, are discussed.

10118-3, Session 1

Commercial quantities of ultrasmall fluorescent nanodiamonds containing color centers *(Invited Paper)*

Olga Shenderova, Nicholas Nunn, Marco Torelli, Gary E. McGuire, Adámas Nanotechnologies, Inc. (United States)

Nanodiamond (ND) particles have recently emerged as a key platform for many sectors of nanoscience and nanotechnology due to their outstanding mechanical performance, biocompatibility and distinctive optical properties, a combination of assets not often met in the nanoworld. Optically active NDs remain one of the most popular research topics mainly due to the photoluminescent properties of crystallographic defects in the diamond lattice, referred to as color centers. Recently our group succeeded in large scale production of fluorescent NDs containing nitrogen-vacancy (NV) color centers in a hundred of grams batches. Production of fractions of ND-NV with median sizes ranging between 10 and 100 nm was achieved. Relative brightness of nanoparticles of different sizes and surface termination will be summarized. Functionalization of small size ND-NV with biomolecules preventing their aggregation will be demonstrated and stability in cell culture media discussed. Small size biofunctionalized nanodiamonds have perspectives as highly photostable and non-toxic fluorescent labels in life science applications.

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10118-4, Session 2

Continuous-variable quantum optical experiments in the time domain using squeezed states and heralded non-Gaussian states *(Invited Paper)*

Jun-ichi Yoshikawa, Yosuke Hashimoto, Hisashi Ogawa, The Univ. of Tokyo (Japan); Shota Yokoyama, The Univ. of New South Wales (Australia); Yu Shiozawa, Takahiro Serikawa, Akira Furusawa, The Univ. of Tokyo (Japan)

In continuous-variable quantum optical experiments, quantum entanglement in Gaussian states is deterministically created, which is in strong contrast to photonic qubit post-selection experiments. Furthermore, number-basis measurements on a part of entangled states enable heralded creation of non-Gaussian states. We are recently shifting to time-domain processing of fast continuous-variable signals, aiming at fast and large-scale measurement-based quantum information processing. This direction is naturally compatible with heralded non-Gaussian states, which are created in a wave-packet localized around the photon detection timing.

Here we show our recent experimental progress, mainly regarding the following three.

First, we have succeeded in creating ultra-large-scale quantum entanglement with full inseparability, where optical qumodes are multiplexed in the time domain.

Second, we are developing a concatenated optical cavity system which can store and release heralded quantum states. With this memory system, the release timing of heralded quantum states is controlled, by which multiple quantum states can be synchronized to some extent. In our results, the released single photon states have a negative region in their Wigner function as an evidence of strong non-classicality.

Third, we tailor the longitudinal modes of heralded quantum states, by which the necessary filtration of measured continuous-variable signals is achievable in real time. This real-time acquisition is aiming at future nonlinear feedforward in complicated quantum gates.

The above three are significant results toward large-scale continuous-variable quantum information processing, which potentially processes encoded qubit information deterministically.

10118-5, Session 2

Intramode encoding of continuous-variable quantum information in a single optical parametric oscillator *(Invited Paper)*

Olivier Pfister, Univ. of Virginia (United States)

Quantum information can be encoded in a scalable manner over the continuous variables (CV) that are the canonically conjugate quantum amplitudes of the electromagnetic field, which are mathematical equivalents of the position and momentum of the quantum harmonic oscillator. Previous results in our group in Charlottesville and the groups of Akira Furusawa in Tokyo, of Nicolas Treps in Paris, and of Ping-Koy Lam in Canberra, have shown that CV quantum information is massively scalable. In addition, Nicolas Menicucci in Melbourne has shown that there exists a fault tolerance threshold for CV quantum computing with the Gottesman-Kitaev-Preskill qubit error encoding. Here, we report on our exploration of the extension of scalable CV encoding by way of intramode, rather than intermode, squeezing and entanglement. As is well known, single-mode squeezing can only be considered along with the “quasi-mode” approximation which assimilates the modes of the optical parametric oscillator cavity used in the experiment to delta functions. As Hans Bachor and Tim Ralph noted, when one ambles beyond this approximation, single-mode squeezing can be described as intramode two-mode squeezing. Here, we aim at generalizing this situation to the case of multipartite entangled cluster states.

10118-6, Session 2

A single-photon subtractor for multimode quantum states *(Invited Paper)*

Nicolas Treps, Clément Jacquard, Young Sik Ra, Univ. Pierre et Marie Curie (France); Jonathan D. Roslund, Univ Pierre et Marie Curie (France); Adrien Dufour, Claude Fabre, Univ. Pierre et Marie Curie (France)

The nature of a quantum network, in particular in the continuous variable regime, is governed not only by the light quantum state but also by the measurement process. It can then be chosen after the light source has been generated. Multimode entanglement is not anymore an intrinsic property of the source but a complex interplay between source, measurement and eventually post processing. This new avenue paves the way for adaptive and scalable quantum information processing. However, to reach this ambitious goal, multimode degaussification has to be implemented.

Single-photon subtraction and addition have proved to be such key operations, but are usually performed with linear optics elements on single-mode resources. We present a device able to perform mode dependant non Gaussian operation on a spectrally multimode squeezed vacuum states. Sum frequency generation between the state and a bright control beam whose spectrum has been engineered through ultrafast pulse-shaping is performed. The detection of a single converted photon heralds the success of the operation.

The resulting multimode quantum state is analysed with standard homodyne detection whose local oscillator spectrum is independently engineered. The device can be characterized through quantum process tomography using weak multimode coherent states as inputs. Its single-mode character can be quantified and its inherent subtraction modes can be measured.

The ability to simultaneously control the state engineering and its detection ensures both flexibility and scalability in the production of highly entangled non-Gaussian quantum states.

10118-7, Session 2

Quantum information with highly-accessible continuous variable state of light: local oscillators and long-range quantum networks *(Invited Paper)*

Raphael C. Pooser, Oak Ridge National Lab. (United States)

Continuous variables (CV) have become important across all facets of quantum information. From quantum sensing to quantum computing to quantum key distribution, the benefits of deterministic quantum state generation clearly make a compelling case to seek full CV-based quantum information solutions from top to bottom. Long range quantum networks have become of interest for their potential use in all three quantum information scenarios: second generation, distributed quantum sensors over quantum networks, multi-user QKD protocols across long range networks, and distributed quantum computing. However, a long range CV quantum network is impossible without overcoming two major roadblocks. First, to enable quantum state measurement or tomography at network nodes, coherent detection is required, which itself requires sending a powerful local oscillator across the network. Sending such a local oscillator across long distances presents a practical limitation: it cannot coexist on the same network infrastructure as with quantum signals. Second, very long range networks require robust quantum states and third-generation quantum repeaters, which themselves require a nonGaussian gate in the CV world. We will present our recent results on long range CV network generation made possible by feed forward phase recovery schemes for "locally" generated local oscillators. In addition, we will present our work on deterministic quantum network generation with highly accessible, cost effective, integrated sources of quantum entanglement. Finally, in order to enable all applications across true quantum networks, a non Gaussian quantum gate is required. We will outline our proposed cubic phase gate and our experimental progress towards achieving this goal.

10118-8, Session 2

Recent advances in quantum computation with continuous-variable cluster states

Rafael N. Alexander, The Univ. of Sydney (Australia)

I will present an overview of some recent results on continuous-variable cluster states, including compact methods for generating them and how they can be used for fault-tolerant measurement-based quantum computation. Recent experiments have demonstrated the unprecedented scalability of cluster states that have macronode-based graphs---meaning that each graph site is composed of multiple modes. I will describe tailored measurement-based protocols on these states that allow for more flexible and compact quantum circuits to be implemented. By adding special ancilla states, I show how noise due to finite squeezing effects can be dealt with via quantum error-correction, thereby enabling fault tolerance.

10118-9, Session 3

Photonic quantum computing *(Invited Paper)*

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

Of the various approaches to quantum computing, photons are appealing for their low-noise properties and ease of manipulation at the single photon level; while the challenge of entangling interactions between photons can be met via measurement induced non-linearities. However, the real excitement with this architecture is the promise of ultimate manufacturability: All of the components---inc. sources, detectors, filters, switches, delay lines---have been implemented on chip, and increasingly sophisticated integration of these components is being achieved. We will discuss the opportunities and challenges of a fully integrated photonic quantum computer.

10118-10, Session 3

Shared nonlocal correlations: Bell measurements and randomness *(Invited Paper)*

Geoff J. Pryde, Griffith Univ. (Australia)

Entanglement is a key resource for remote quantum information science tasks. The gold standard in verifying remote shared entanglement is the violation of a loophole-free Bell inequality, which allows device-independent quantum key distribution, for instance. However, such a violation is very difficult over long distances. Optics provides a useful method for distributing quantum signals, but fibre, atmospheric or diffraction losses grow rapidly, opening the detection loophole even when high-efficiency detectors are used.

Quantum steering (also called EPR steering) is an asymmetric protocol that provides enhanced loss tolerance with the extra assumption that one party, and his apparatus, is trusted. Here we consider the case where channel loss is so high that even a loss-tolerant quantum steering protocol cannot be completed directly. This might correspond to attempting the protocol over many tens, or hundreds, of kilometres of optical fibre. We design and experimentally demonstrate a protocol that allows quantum steering to be completed even in this case. We use entanglement swapping to herald the presence of half of an entangled pair, after a lossy channel, and then complete the steering protocol using this event-ready detection.

We also experimentally demonstrated how quantum measurements (Bell measurements) can be used to process randomness. It is theoretically known [e.g. Dale et al, Nature Comms 6, 8203 (2015)] that certain tasks in reshaping uniform probability distributions are computationally difficult, and that the quantum approaches to this task can provide a large advantage. We demonstrate how to do this quantum processing in an optical system.

10118-11, Session 3

High-speed continuous-variable quantum key distribution over atmospheric turbulent channels

Zhen Qu, Ivan B. Djordjevic, The Univ. of Arizona (United States)

In this protocol , Alice randomly draws quaternary variables, each corresponding to a specific coherent state. The repetition rate used for quantum key distribution is 12.5 GHz. To compensate for the phase noise, a local oscillator (LO) signal is polarization multiplexed with the signal and co-propagates through the atmospheric turbulent channel. The atmospheric turbulence is emulated by two spatial light modulators on which two randomly generated azimuthal phase patterns from Andrews spectral density are recorded. At Bob's side, a heterodyne detection is performed to measure both quadratures. In order to realize secure transmission over a channel with more than 3 dB loss, reverse reconciliation is used by Alice and Bob, and the reconciliation efficiency can be improved by the-state-of-art LDPC code in a low SNR scenario. Finally, it will be demonstrated that a secure key rate of 1 Gbit/s can be achieved in the proposed discrete modulation based continuous-variable quantum key distribution (CV-QKD) system.

10118-12, Session 4

Quantum state estimation and discrimination *(Invited Paper)*

Shigeki Takeuchi, Ryo Okamoto, Kyoto Univ. (Japan); Takafumi Ono, Univ. of Bristol (United Kingdom); Koichi Yamagata, Chuo Univ. (Japan); Akio Fujiwara, Osaka Univ. (Japan); Satoshi Hara, National Institute of Informatics (Japan); Takashi Washio, Osaka Univ. (Japan)

The estimation and the discrimination of quantum states are important for quantum information, and is also indispensable to quantum metrology.

In the first part, we report adoptive quantum state estimation, which provides the most accurate estimation using an optimal measurement basis for each measurement [1]. The angle of a half wave plate (HWP) that initializes the linear polarization of input photons is estimated using AQSE. A sequence of AQSE is carried out with 300 input photons, and the sequence is repeated 500 times. The statistical analysis verifies the strong consistency and asymptotic efficiency of AQSE.

In the second part, we introduce quantum state data mining where the erroneous states (density matrices) are discriminated from the normal ones efficiently using machine learning method. We developed a new data mining method named `Erroneous Deviation Detection for Density matrices (ED3)' for quantum density matrices by extending a previously reported method [2]. We compare ED3 and a naive method, in which the erroneous states are distinguished by the trace distance from the average of the states. We show that ED3 has a significant advantage over the naive method for numerical simulation data and real experimental data.

We will also report our most recent results on these topics.

[1] R. Okamoto, M. Iefuji, S. Oyama, K. Yamagata, H. Imai, A. Fujiwara, and S. Takeuchi, Phys. Rev. Lett. 109, 130404 (2012).

[2] S. Hara, T. Ono, R. Okamoto, T. Washio, and S. Takeuchi, Phys. Rev. A 89, 022104 (2013).

10118-13, Session 4

Advances in quantum nonlinear optics *(Invited Paper)*

Robert W. Boyd, Univ. of Ottawa (Canada)

This presentation first reviews the historical development of the field of nonlinear optics, starting from its inception in 1961. It then reviews some of its more recent developments, including especially how nonlinear optics has become a crucial tool for the developing field of quantum technologies. Fundamental quantum processes enabled by nonlinear optics, such as the creation of squeezed and entangled light states, are reviewed. We then illustrate these concepts by means of specific applications, such as the development of secure communication systems based on the quantum states of light. We are also interested in studying the properties of structured light fields. These structured light beams have recently been shown to possess exotic properties of their own, such as vacuum propagation velocities differing from the light velocity c for plane waves. These beams can also be tailored in such a way that they carry orbital angular momentum, which can be used to apply a torque to mechanical objects and as a carrier of information in a classical and quantum telecommunication system. Light can carry angular momentum both by means of its spin angular momentum (as manifested for example in circular polarization) and by means of its orbital angular momentum (OAM), whose origin is a helical structure of its wavefront. The orbital angular momentum of light has recently been recognized to constitute a crucial attribute for many photonic technologies, including the trapping and manipulation of small particles and for multiplexing in optical telecommunication. In this presentation we review some of the fundamental properties of OAM including its quantum features such as entanglement. We then go on to describe a secure telecommunication system in which information is encoded in OAM, and which can carry more than one bit of information per photon.

10118-14, Session 4

Practical quantum repeaters for ultra-long distance quantum communication *(Invited Paper)*

Pieter Kok, Scott Vinay, The Univ. of Sheffield (United Kingdom)

We present a protocol for a quantum repeater to distribute entanglement over large distances. We show how one can use only existing and widely available techniques and equipment to create high-fidelity entanglement between adjacent stations, perform deterministic effective Bell measurements and distil the resulting states. A thorough analysis of the relevant errors, taking only the worst case scenarios, gives a lower bound for secret-key generation which is at a higher rate and for longer distances than that of other protocols. We show that a lower bound for the reachable distance is on the order of 3000km.

10118-15, Session 4

Time-optimal quantum control via differential geometry *(Invited Paper)*

Xiaoting Wang, Louisiana State Univ. (United States); Michele Allegra, Scuola Internazionale Superiore di Studi Avanzati (Italy); Kurt A. Jacobs, U.S. Army Research Lab. (United States); Masoud Mohseni, Google (United States); Seth Lloyd, Massachusetts Institute of Technology (United States); Cosmo Lupo, Univ. of York (United Kingdom)

Time-optimal control of quantum dynamics is important for quantum

computing, as it provides a direct method to reduce the decoherence effect. It has been found that the time-optimal control protocol can be described by the quantum brachistochrone equation. However, solving this equation turns out to be numerically difficult. In this work, we show that the quantum brachistochrone problem can be recast as that of finding geodesic paths in the space of unitary operators. We find this brachistochrone-geodesic connection to have broad applications, as it opens up minimal-time control to the tools of geometry. In particular, we use it to obtain a fast numerical method to solve the brachistochrone equation. As an application, the time-optimal control protocol can be realized experimentally on spin qubits in solids.

10118-16, Session 5

Multidimensional tomography of an entangled photon-pair source using stimulated emission *(Invited Paper)*

Bin Fang, Univ. of Illinois at Urbana-Champaign (United States); Marco Liscidini, Univ. degli Studi di Pavia (Italy); John E. Sipe, Univ. of Toronto (Canada); Virginia O. Lorenz, Univ. of Illinois at Urbana-Champaign (United States)

Characterizing photon-pair-based sources typically involves performing quantum state tomography, which relies on counting coincidences for a series of projective measurements. However, as sources have necessarily low photon count rates, making such measurements in more than one degree of freedom is difficult due to low signal-to-noise ratio. We demonstrate that stimulated emission tomography (SET) is capable of efficiently revealing the multidimensional correlations of an entangled photon-pair source with high signal-to-noise ratio and detailed resolution.

By relying on the connection between spontaneous and stimulated processes, SET enhances the signal measured for the same projective measurements as in quantum state tomography, with a signal strength many orders of magnitude higher due to the use of a seed to stimulated the process. We measure the frequency-resolved polarization density matrix of an optical fiber photon-pair source using a seed that is narrowband compared to the variation of the density matrix versus frequency. This results in a frequency-resolved polarization density matrix composed of thousands of individual polarization density matrices, one for each frequency pair. We find that analyzing the SET result reveals detailed information about correlations between the joint polarization and joint frequency degrees of freedom. This technique can be applied to other entangled photon-pair sources, enabling swift characterization of quantum sources for engineering and optimization.

10118-17, Session 5

Creation and detection of high-dimensional entangled states for quantum communication *(Invited Paper)*

Andrew Forbes, Univ. of the Witwatersrand (South Africa)

High-dimensional entangled states offer the promise of increased data transfer and better security than conventional two-dimensional (qubit) systems, and thus realising and detecting such states is a topical and actively researched field. Yet despite the promise, few studies have managed to extend the tools beyond qubits. In this talk I will review the present state-of-the-art in creating and detecting high-dimensional quantum states based on the spatial modes of light. In particular, I will consider tools to engineer such states, present new results on their propagation through turbulence, and then discuss the challenges in the detection schemes that presently are used. Finally, I will show how it is possible to perform entanglement swapping and teleportation of such states, essential tools to cover long distances in a secure quantum communication network.

10118-18, Session 5

On chip analysis of path-polarization hyperentangled cluster photon states *(Invited Paper)*

Mario Arnolfo Ciampini, Sapienza Univ. di Roma (Italy); Adeline Orieux, Sapienza Univ. di Roma (Italy) and Télécom ParisTech (France); Stefano Paesani, Caterina Vigliar, Valeria Cimini, Sapienza Univ. di Roma (Italy); Roberta Ramponi, Roberto Osellame, CNR-Istituto di Fotonica e Nanotecnologie (Italy) and Politecnico di Milano (Italy); Giacomo Corrielli, Politecnico di Milano (Italy); Andrea Crespi, Politecnico di Milano (Italy) and CNR-Istituto di Fotonica e Nanotecnologie (Italy); Mauro Paternostro, Queen's Univ. Belfast (United Kingdom); Marco Barbieri, Univ. degli Studi Roma Tre (Italy); Paolo Mataloni, Sapienza Univ. di Roma (Italy)

Encoding many qubits in different degrees of freedom (DOFs) of single photons is one of the routes towards enlarging the Hilbert space spanned by a photonic quantum state. Hyperentangled photon states (i.e. states showing entanglement in multiple DOFs) have demonstrated significant implications for both fundamental physics tests and quantum communication and computation. Increasing the number of qubits of photonic experiments requires miniaturization and integration of the basic elements and functions to guarantee the set-up stability. This motivates the development of technologies allowing the control of different photonic DOFs on a chip. Femtosecond laser writing on glass techinique allows the preservation of both path and polarization of photon states and precise control of both degrees of freedom due to the low birifringence of the substrate. In this work we demonstrate the contextual use of path and polarization qubits propagating within an integrated quantum circuit by characterizing an hyperentangled state. We demonstrate the quality of the quantum state by engineering a four-qubit linear cluster built on both DOFs and exploiting it to perform the Grover's search algorithm according to the one-way quantum computation model. In addition we test the non-local properties of the cluster state and its usefullness as resource for quantum information protocols by assessing the strength of the links between qubits using multipartite non-locality inequalities based tests. Our results pave the way towards the full integration on a chip of hybrid multiqubit multiphoton states.

10118-19, Session 5

Non-local correlations in a hyper-entangled circuit

David H. Hughes, Air Force Research Lab. (United States); Reinhard K. Erdmann, Advanced Automation Corp. (United States)

Non-local correlations in the degrees of freedom of an entangled photon pair propagating through a simple optical circuit, assumed closed and without loss, are modeled. Distinguishable by frequency, the two photons enter the circuit in a rotationally invariant joint state. Operated on by a beam splitter, a Lyot filter, and possibly a polarization beam splitter, the output joint state is non-rotationally invariant. An application closely related to the Ekert protocol for key distribution is discussed. The output state is mapped onto a representation in terms of possible measurement outcomes as a function of the two receivers' frames of measurement. The QKD protocol is most efficient when the two users measure in the same frame by using Horace Yuen's pre-shared key paradigm, KCQ, or keyed communication in quantum noise. Several standard methods for determining entanglement are computed.

10118-37, Session PWed

Plasmonic superradiance of two emitters near metal nanorod

Igor E. Protsenko, Alexander V. Uskov, P.N. Lebedev Physical Institute (Russian Federation); Xue-wen Chen, School of Physics, Huazhong University of Science and Technology (China); Hongxing Xu, Wuhan Univ. (China)

We consider two-level transitions of N emitters (as q-dots) coupled with non-radiative plasmonic mode of metal nanorod. External field or injected current pumps transitions incoherently (as in lasers or LEDs); emitters excite plasmonic mode through near field. We show, the excitation efficiency of plasmons grows with N faster than ~ N: because of synchronization of emitters by electric field of plasmonic mode, similar as electromagnetic field synchronizes emitters at superradiance (SR) in free space. Density of states of electric field near the nanorod is higher than in free space, so such "plasmonic" SR is more efficient than free space SR. We model plasmonic SR in dissipative environment: at stationary incoherent pump, absorption in nanorod and with dephasing of emitters. We use fully quantum mechanical model at adiabatic elimination of plasmonic mode. For N=2 emitters we found up to 15% increase in the relative quantum efficiency (RQE) of excitation of plasmons per emitter. RQE increase will grow further with N>2 [http://arxiv.org/abs/1604.08302]. Population inversion of emitter transitions is necessary for RQE increase; SR leads to RQE decrease otherwise. Observation of plasmonic SR of few emitters near metal nanorod may be good "proof of principle" experiment on efficient quantum SR in dissipative environment: one can register correlations in blinking of emitters or increase in efficiency of generation of light per emitter. Possible applications of plasmonic SR: for excitation (also by injection current), control of non-radiative modes in plasmonic wavequides; for fast and efficient single photon sources; for lowing threshold of plasmonic nanolasers.

10118-38, Session PWed

Statistical quadrature evolution by inference for continuous-variable quantum key distribution

Laszlo Gyongyosi, Budapest Univ. of Technology and Economics (Hungary) and Hungarian Academy of Sciences (Hungary); Sandor Imre, Budapest Univ. of Technology and Economics (Hungary)

We define the statistical quadrature evolution (QE) method for multicarrier continuous-variable quantum key distribution (CVQKD). A multicarrier CVQKD protocol uses Gaussian subcarrier quantum continuous variables (CVs) for information transmission. The QE scheme utilizes the theory of mathematical statistics and statistical information processing. The QE model is based on a statistical inference method to provide a minimal error estimate of the CV state quadratures. The QE block evaluates a unique and stable estimation of the non-observable continuous input from the measurement results. The QE method minimizes the overall expected error by an estimator function and provides a viable, easily implementable, and computationally efficient way to maximize the extractable information from the observed data. The QE framework can be established in an arbitrary CVQKD protocol and measurement setting and is implementable by standard low-complexity functions, which is particularly convenient for experimental CVQKD.

10118-39, Session PWed

Integrated-optics-based quantum-communication devices

Rohit K. Ramakrishnan, Shafeek A. Samad, Indian Institute of Science (India); Yadunath Thamerassery Illam Rameswaran, Indian Institute of Science (India) and National Institute of Technology Karnataka (India); Partha P. Das, National Institute of Technology Karnataka, Surathkal (India); Srinivas Talabattula, Indian Institute of Science (India)

Quantum communication or more specifically quantum information processing is considered as the future of information science and technology. In this paper we propose a scheme to implement quantum communication at the device level using integrated optics. In order to realize this we use the photon angular momentum approach. Photons carry Spin Angular Momentum (SAM) and Orbital Angular Momentum (OAM). OAM enables us to transmit an arbitrary number of bits per photon. We extend this idea to multi-photon states. Interferometric methods are used to generate photon states with different angular momentums. We choose OAM of photons along with combined OAM-SAM state for implementation. Entanglement-assisted protocols using OAM-SAM are investigated which can be used for secure key distribution over free-space optical and few-mode fiber channels. We describe methods to make deterministic universal quantum gates and realize the implementation of the quantum communication protocols using the same. We analyze the aspects of quantum communications through free space as well as optical fibers. Even though much significant research advances have happened in the area of QKD, the major issue of low data rate is still not addressed. This method increases the information content of photons thus increasing on the data rates. This leads to high dimensional quantum key distribution (HD-QKD) which is encoding into a larger state space, such as multiple levels of a continuous variable of a single photon, thus enabling the system to achieve higher photon information efficiency (bits/photon) and potentially higher key rate (bits/second).

10118-40, Session PWed

All-fiber photon-pair source at telecom wavelengths

Erik N. Christensen, Mario A. Usuga Castaneda, Karsten Rottwitt, DTU Fotonik (Denmark)

Single photon sources are of interest for quantum computing, quantum key distribution (QKD) and quantum communications. In particular, producing single photons at telecommunications wavelengths is valuable for QKD protocols and would enable realizing the quantum internet. The preferred method for their generation has long been spontaneous down conversion in bulk crystals, which suffers from connection loss to fiber networks. In-fiber spontaneous four-wave mixing provides a viable alternative as a photon pair source due to to being compatible with existing fiber networks.

We present an all-fiber photon pair source based on degenerate Four-wave mixing in a 400 m Highly-Nonlinear fiber, with signal and idler wavelengths generated at 1551 nm and 1559 nm respectively.

The source consists of CW pump laser operating at 1554.75 nm, which is slightly detuned from the zero dispersion into the normal dispersion regime.

After pair generation in the highly-nonlinear fiber, three arrayed waveguide gratings are employed to spatially separate signal and idler, and provides a 120 dB pump power reduction.

Firstly the source is modeled and experimentally characterized in the well known classical regime of stimulated four-wave mixing.

The effect of fiber cooling on spontaneous Raman scattering is modeled and characterized, and a 30% reduction in Raman noise is found when cooling the fiber to -77 C.

In the quantum regime the photon pair generation bandwidth is simulated, and the coincidence to accidental ratio and second order coherence function are measured. An increase in the coincidence to accidental ratio is observed when cooling the fiber.

10118-41, Session PWed

Synchronized optical cavities for quantum optics

Rosa Tualle-Brouri, Martin Bouillard, Guillaume Boucher, Bhaskar Kanseri, Institut d'Optique Graduate School (France)

Among the numerous candidates for ultimately achieving a quantum computer, quantum optics presents many significant strengths as light can be efficiently isolated from the environment. This is at least true when considering free space propagation between high reflectivity mirrors. For instance, a standard cavity of high finesse with a low-loss active insertion/extraction system could be a good candidate for a high-fidelity quantum memory. Another advantage of optical technologies is the possibility to integrate most of the devices implied in quantum computing protocols: for instance, photodiodes can be merged by thousands in integrated circuits. This could be a great advantage for the design of a scalable architecture.

We will discuss the potential of synchronized optical cavities in the pulsed regime to generate complex mesoscopic quantum states and to implement quantum operations following recent theoretical proposal [NJP 16, 053001, 2014]. Single-photons are a main resource for these targeted protocols, but pure states in well-defined spatio-temporal modes are required in order to perform relevant homodyne measurements [PRL 114, 193602, 2015]. We will present a setup for high-rate single-photons generation, based on exaltation cavities in the pulsed regime, and discuss the way to synchronize this source with another cavity in order to have a quantum memory and to implement new kinds of innovative quantum protocols.

10118-42, Session PWed

Hyper-entanglement for quantum-key distribution

Bienvenu I. Ndagano, Isaac Nape, Stirling Scholes, Melanie McLaren, Carmelo Rosales-Guzman, Univ. of the Witwatersrand (South Africa); Thomas Konrad, Univ. of KwaZulu-Natal (South Africa); Andrew Forbes, Univ. of the Witwatersrand (South Africa)

With the development of quantum cryptography (QC), provably secure communication is now within our grasp. Using photons in particular, a multitude of QC protocols have been implemented, whereby information was encoded on the polarization degree of freedom (DoF) in order to generate an encryption key. Over time, we predict that the demand with QC systems will grow, together with the need for even more sophisticated protocols. One of the many challenges within sight, will undoubtedly be faster key generation. Encoding information in the polarisation DoF is certainly simple and practical with current optical elements, however it comes with a fundamental limit, only one bit of information can be encoded on a single photon. Here, we propose a way around this obstacle, the use of higher-dimensional hybrid space-polarization photonic states, where the spatial DoF is the quantized, infinite dimensional, orbital angular momentum of photons. The higher dimensionality allows one to pack more information into photons. Furthermore, these states have classical analogues in the form of vector vortex modes that can be generated by manipulating the geometric phase of light with custom designed wave plates. We experimentally demonstrate, on one hand, the simulation of our high dimensional QC protocol using vector vortex modes, and show an increase in information capacity close to the Shannon limit. On the other hand, we implement a higher dimensional QC protocol using hybrid space-polarization photonic states, and show an increase in information capacity well beyond the current state-of-the-art for identical dimensionality.

10118-43, Session PWed

Spectral correlation and interference in continuous-wave non-degenerate photon pairs at telecom wavelengths

Paulina S. Kuo, Thomas Gerrits, Varun B. Verma, Sae Woo Nam, National Institute of Standards and Technology (United States)

We use single-photon, fiber-assisted spectroscopy to study indistinguishability in our new polarization entangled photon pair source. The source is based on spontaneous parametric down-conversion in a domain-engineered, periodically poled lithium niobate (PPLN) crystal. Using a continuous-wave pump at 775 nm wavelength, we use single-photon, fiber-assisted spectroscopy to measure the spectrum of the generated photons near 1533 nm and 1567 nm. We also observed an interference signature, which is related to the spectral correlations between photons in a Hong-Ou-Mandel interferometer at non-zero time-delay. We can create and erase the interference signature using a half-wave plate, which modified the polarization states of the down-converted photons. We show that the interference is only present when there is polarization indistinguishability between the two down-conversion paths available in our domain-engineered PPLN crystal. We believe that this measurement is a useful diagnostic towards measuring indistinguishability in the source and characterizing the usefulness of the source for generated entangled photon pairs. In future work, we plan to measure the polarization correlations in the source, and relate this to results presented in this work. We believe our entangled photon pair source can serve as a telecom-compatible building block for hybrid quantum networks.

10118-20, Session 6

High-resolution spectroscopy of single rare earth ions *(Invited Paper)*

Vahid Sandoghdar, Max-Planck-Institut für die Physik des Lichts (Germany)

Recently, we showed the first high-resolution spectroscopy and manipulation of single Pr^{3+} ions in the solid state using rare-earth doped crystals. The special feature of these systems is access to the hyperfine splitting caused by the interaction of the 4f electrons and the nucleus, leading to sets of sublevels with exceptionally long coherence times at cryogenic temperatures, on the order of minutes and hours. This ground state splitting can serve as a lambda level scheme, a key ingredient for many prospective applications in quantum optics, in particular for qubit storage and manipulation. In this presentation, we discuss our latest results and future challenges in reducing spectral diffusion and line broadening down to the expected natural linewidth, prospects for the use of microcavities or plasmonic nano-antennas to enhance the photon yield, and schemes for on-chip integration.

10118-21, Session 6

Quantum nanophotonic devices based on rare-earth-doped crystals *(Invited Paper)*

Andrei Faraon, Tian Zhong, Jonathan M. Kindem, Evan Miyazono, Ioana Craiciu, Jake H. Rochman, John Bartholomew, California Institute of Technology (United States)

Quantum light-matter interfaces that reversibly map the quantum state of photons onto the quantum states of atoms, are essential components in the quantum engineering toolbox with applications in quantum communication, computing, and quantum-enabled sensing. In this talk I present our progress towards developing on-chip quantum light-matter interfaces based on nanophotonic resonators fabricated in rare-earth-doped crystals known to exhibit the longest optical and spin coherence times in the solid state. We recently demonstrated coherent control of neodymium (Nd3+) ions coupled to yttrium orthosilicate Y2SiO5 (YSO) photonic crystal nano-beam resonator. The coupling of the Nd3+ 883 nm 4I9/2-4F3/2 transition to the nano-resonator results in a 40 fold enhancement of the transition rate (Purcell effect), and increased optical absorption (~80%) - adequate for realizing efficient optical quantum memories via cavity impedance matching. Optical coherence times T2 up to 100 ?s with low spectral diffusion were measured for ions embedded in photonic crystals, which are comparable to those observed in unprocessed bulk samples. This indicates that the remarkable coherence properties of REIs are preserved during nanofabrication process. Multi-temporal mode photon storage using stimulated photon echo and atomic frequency comb (AFC) protocols were implemented in these nano-resonators. Our current technology can be readily transferred to Erbium (Er) doped YSO devices, therefore opening the possibility of efficient on-chip optical quantum memory at 1.5 ?m telecom wavelength. Integration with superconducting qubits can lead to devices for reversible quantum conversion of optical photons to microwave photons.

10118-22, Session 6

Hybrid microring resonator devices for rare-earth quantum-light matter interfaces

Ioana Craiciu, Evan Miyazono, Tian Zhong, Jonathan M. Kindem, Andrei Faraon, California Institute of Technology (United States)

Rare earth quantum light-matter interfaces (QLMIs) are uniquely suited for various quantum communication applications, including quantum memories and quantum optical to microwave transducers. Among rare earths, erbium QLMIs are particularly appealing due to erbium's long lived telecom wavelength resonance, allowing integration with existing optical communication technology and infrastructure. Micro-resonator QLMIs have various advantages over bulk rare earth crystal memories. They provide the opportunity for on-chip integration; for example, optical resonators can be integrated with microwave resonators for quantum optical-microwave transduction. For spectral hole-burning based quantum memories, coupling rare earth ions to a resonator can provide improved memory initialization via Purcell enhancement of optical lifetimes, while impedance matching the resonator to the ions can raise the theoretical memory efficiency to 100%.

We present hybrid nanoscale quantum light matter interfaces in the form of amorphous silicon ring resonators on yttrium orthosilicate (YSO) substrate doped with erbium ions. While working with rare earth crystal hosts can be challenging, the fabrication process for these devices is simple and robust, using traditional thin film fabrication technologies. Our devices have measured quality factors of over 105 in the 11 μm diameter rings, and evanescent coupling to an ensemble of erbium ions characterized by a cooperativity of 0.54. We present simulation and experimental results of the optical properties of these cavities, and their coupling to erbium ions, including a demonstration of Purcell enhancement of the erbium telecom transition. We then analyze their potential as quantum memories and in optical to microwave transducers.

10118-23, Session 6

Towards an efficient nanophotonic platform integrating quantum memories and single qubits based on rare-earth ions

Tian Zhong, Jonathan M. Kindem, John G. Bartholomew, Jake H. Rochman, Ioana Craiciu, Evan Miyazono, Andrei Faraon, California Institute of Technology (United States)

The integration of rare-earth ions in an on-chip photonic platform would enable quantum repeaters and scalable quantum networks. While ensemble-based quantum memories have been routinely realized, implementing single rare-earth ion qubits remains an outstanding challenge due to its weak photoluminescence. Here we demonstrate a nanophotonic platform consisting of yttrium vanadate (YVO) photonic crystal nanobeam resonators coupled to a spectrally dilute ensemble of neodymium (Nd) ions. The cavity acts as a memory when prepared with spectral holeburning, meanwhile it enables addressing of single ions with high-resolution spectroscopy. For the quantum memory, atomic frequency comb (AFC) protocol was implemented in a 50 ppm Nd:YVO nanocavity cooled to 475 mk. The storage time ranges from 100 to 150 ns. We currently measure a storage efficiency at 0.5% with a 90% efficient WSi superconducting nanowire single photon detector (SNSPD). With optimized device fabrication, we project >10% AFC storage efficiency with a one-sided cavity of Q=20,000. The small mode volume of the cavity results in a peak atomic spectral density of 3 ions per homogeneous linewidth, suitable for probing single ions when detuned from the center of the inhomogeneous distribution. The high-cooperativity coupling of a single ion yields a strong signature (20%) in the cavity reflection spectrum, which is detectable with our efficient SNSPD. We estimate a signal-to-noise ratio exceeding 10 for addressing a single Nd ion at the 879.7nm transition. This, combined with the AFC memory, constitutes a promising platform for preparation, storage and detection of rare-earth qubits on the same chip.

10118-24, Session 6

Broadband photonic quantum interface based on a cavity-protected rare-earth ensemble

Tian Zhong, Jonathan M. Kindem, Jake H. Rochman, Andrei Faraon, California Institute of Technology (United States)

Rare-earth ions doped in crystals are renowned for their excellent coherence properties and large inhomogeneous broadening, which make them ideal for quantum interfaces with broadband photons. These properties have made them one of the leading technologies in quantum optical memories and a promising candidate for optical-to-microwave conversion. To take advantage of the full bandwidth of the rare-earth ensemble, one must overcome the decoherence of a broadband collective excitation due to inhomogeneous broadening. To this end, techniques based on controllable rephasing, such as atomic frequency comb (AFC) or controlled reversible inhomogeneous broadening (CRIB) memories, have been developed with great success. Recently, an alternative method was proposed to suppress the decoherence of an inhomogeneous ensemble via strong coupling to a cavity, a phenomenon called cavity protection. This technique has been demonstrated in the microwave domain with an NV spin ensemble, but has not been demonstrated in the optical domain. Here, we demonstrate cavity protection in the optical domain at the single photon level using an ensemble of rare earths ions coupled to a nanophotonic resonator. The reduction in decoherence due to the cavity-protection effect enables transfer of ultrafast (~50 GHz) frequency qubits into the collective ion excitation and retrieval with 98.7% fidelity. Building on these results to transfer these excitations to long-lived spin states would enable broadband, on-demand quantum memories. Furthermore, this works compliments the work done coupling rare-earths to superconducting resonators in the microwave regime with potential for applications in optical-to-microwave transducers.

10118-25, Session 7

Rare-earth-doped crystals for quantum communications *(Invited Paper)*

Wolfgang Tittel, Univ. of Calgary (Canada)

Future quantum networks will allow the secure distribution of encryption keys over extended distances, blind quantum computing, and networked quantum computers and atomic clocks. I will discuss our experimental work on two key ingredients of such networks: a solid-state storage device for quantum states of light, and a detector that promises detecting the presence of photons without destroying them. Both devices employ a Thulium-doped LiNbO3 crystal cooled to a temperature of around 1K.

10118-26, Session 7

Solid-state spin-wave quantum memories for single photons *(Invited Paper)*

Hugues de Riedmatten, ICFO - Institut de Ciències Fotòniques (Spain)

Photonic quantum memories are important devices in quantum information science, and are crucial for several applications including quantum repeaters and quantum networks. Rare-earth (RE) doped crystals are promising candidates as quantum memories for light as they offer coherence properties comparable to those of atomic systems, but free of the drawbacks deriving from atomic motion. The research on RE based quantum memories has been so far mostly focused on the mapping of photonic quantum bits to optical collective excitations, but this leads to short lived and mostly pre-determined storage. However, some RE ions, as Praseodymium and Europium, exhibit the suitable energy level scheme, with three long-lived hyperfine ground states, to enable the spin-wave storage by transferring the collective optical excitations into collective spin excitations. Proof of principle spin-wave quantum memories have been reported in rare-earth doped crystals, using weak coherent states as input [1,2]. Here, I will present our recent results on the realization of multimode spin-wave quantum memories in a Praseodymium doped crystal, using non-classical input light.

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[2] P. Jobez, C. Laplane, N. Timoney, N. Gisin, A. Ferrier, P. Goldner, and M. Afzelius, Coherent Spin Control at the Quantum Level in an Ensemble-Based Optical Memory, Phys. Rev. Lett. 114, 230502 (2015)

10118-27, Session 7

Laser-written waveguides in rare-earth-doped crystal for integrated optical memory applications

Giacomo Corrielli, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Alessandro Seri, Margherita Mazzera, ICFO - Institut de Ciències Fotòniques (Spain); Roberto Osellame, CNR-Istituto di Fotonica e Nanotecnologie (Italy) and ICFO - Institut de Ciències Fotòniques (Italy); Hugues de Riedmatten, ICFO - Institut de Ciències Fotòniques (Spain) and Institució Catalana de Recerca i Estudis Avançats (Spain)

The reversible mapping of quantum states of light in cryogenically cooled rare earth doped crystals, represents one of the most promising routes towards the realization of efficient and high fidelity quantum memories. The miniaturization of these devices in robust and monolithic integrated-optics platforms would be beneficial both in terms of experimental scalability and of enhanced light-matter interaction, arising from the waveguide field confinement.

Here, for the first time, we fabricate single mode channel waveguides for visible light at 606 nm in a Praseodymium-doped Yttrium Orthosilicate crystal, which is one of the most employed materials for light storage experiments, thanks to its excellent coherence properties. For the waveguide fabrication, we use the direct technique called femtosecond laser micromachining, in which a femtosecond laser beam is focused inside the crystal volume, and produces a permanent and very localized material modification. In particular, we fabricate the waveguide cladding by inscribing a pair of parallel damage tracks which confine light in the in-between region. With this approach, the waveguide core is not directly exposed to the laser irradiation and consequently its bulk properties result only marginally affected. Measurements of the optical coherence time in waveguide gave results comparable to those obtained in a bulk sample and this confirms that the fabrication procedure does not affect the coherence of the active ions. We performed the storage and the on-demand recall of bright coherent pulses in waveguide, using the atomic frequency comb (AFC) protocol extended to the ground state.

10118-28, Session 7

Quasi-coherent mixing of mechanical excitations in vacuum

Tong Lin, Guangya Zhou, Fook Siong Chau, National Univ. of Singapore (Singapore)

The coherent mixing of mechanical excitations has been demonstrated by the squeezed film effect. However, if the system was placed in air, the mechanical motion is damped causing the low mechanical Q-factors. Herein, we propose another mechanism in vacuum: the combined effect of the optical gradient force and photothermal force in the platform of silicon suspended doubly coupled photonic crystal nanobeam cavities. As the squeezed film effect is minimized, the mechanical Q-factors are improved. Based on the experimental results, the mechanical motions of the two modes were coherent in the low optical pump power regime. They behaved reversibly either in blue detuned or red detuned region. In the high optical pump power regime, a quasi- EIT phenomenon was observed. This study provide an alternative of achieving quantum information processing.

10118-29, Session 8

Generating quantum correlations between distant quantum-dot spins *(Invited Paper)*

Mete Atatüre, Univ. of Cambridge (United Kingdom)

Optically active semiconductor quantum dots offer high quality spin-photon interfaces for quantum optics applications. This interface can be used to generate distant entanglement between confined spins based on projective measurements. I will review current progress on this topic highlighting the crucial role played by coherent scattering.

10118-30, Session 8

Quantum-dot-based quantum devices *(Invited Paper)*

Lorenzo De Santis, Carlos A. Solanas, Niccolo Somaschi, Ctr. National de la Recherche Scientifique (France); Aristide Lemaitre, Isabelle Sagnes, Valerian Giesz, Loic Lanco, Pascale Senellart, Lab. de Photonique et de Nanostructures (France)

Semiconductor quantum dots (QDs) are promising artificial atoms for quantum information processing: they can generate single photons flying quantum bits; they show single photon sensitivity promising to develop quantum gates and the spin of a carrier in a QD can be a quantum memory. The scalability of a quantum network requires efficient interfaces between stationary and flying quantum bits. In the last few years, our group has made important progresses in this direction using cavity quantum electrodynamics.

With a deterministic positioning of a single QD in a microcavity, we control the QD spontaneous emission on demand [1]. With such technique highly efficient single photon sources with brightness as large as 80% are demonstrated [2]. By minimizing the charge noise around the QD in a gated structure [3], we demonstrate the generation of fully indistinguishable photon. The source brightness is shown to exceed by one or two orders of magnitude the one of a parametric down-conversion source of same quality [4]. Symmetrically, these devices perform as excellent interfaces between a flying quantum bit and a stationary one, where coherent control of a quantum bit can be done when only few photons [5].

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10118-31, Session 8

Silicon-vacancy center in metallic nanoresonators

I-Chun Huang, Harvard Univ. (United States); Srujan Meesala, Harvard School of Engineering and Applied Sciences (United States); Cleaven S. E. Chia, Harvard Univ. (United States); Jeffrey Holzgrafe, Univ. of Cambridge (United Kingdom); Marko Loncar, Harvard School of Engineering and Applied Sciences (United States)

In recent years, silicon-vacancy (SiV–) center has gained significant attention due to its outstanding properties: strong zero-phonon line (ZPL) emission (~70%), robustness to the fabrication process, nearly lifetime limited optical linewidths, and lifetime-comparable spectral diffusions in nano-structures.

Metallic nano-resonator can strongly enhance the spontaneous decay rate and pumping intensity, which is suitable for enhancing single photon emission. In this work, we use circular and bow-tie apertures to engineer the emission of SiV– centers. Simulations show that the Purcell enhancements for circular aperture with diameter of 110 nm and for bowtie aperture with 20 nm gap are ~15 and ~90, respectively. We used e-beam lithography followed by reactive ion etching (RIE) to create diamond pillars with embedded SiV– centers. Next, gold was deposited using e-beam evaporation followed by 650?C annealing for 7 minutes. Finally, sonication and lift-off were performed to get clean diamond gold apertures.

Preliminary measurements show that SiV– centers inside circular apertures can have lifetime as short as 0.2 ns, which represents a ~9-fold reduction over a ~1.8 ns value typical for SiV– in bulk diamond. Given that the non-radiative relaxation might be large in SiV– center, the actual Purcell enhancement should be larger than 9. Interestingly, SiV– transitions inside apertures span a relatively wide wavelength range (10 nm) compared to that of bulk (< 1 nm), likely caused by large local strain introduced by our fabrication process.

10118-32, Session 8

Tunable cavity coupling to the zero phonon line of a nitrogen-vacancy defect in diamond at low temperature

Sam Johnson, Laiyi Weng, Philip R. Dolan, Aurelien A. P. Trichet, Sanmi Adekanye, Yu-Chen Chen, Univ. of Oxford (United Kingdom); Ross Leyman, Paul Hill, Univ. of Strathclyde (United Kingdom); Ben Green, Gavin Morley, Mark E. Newton, The Univ. of Warwick (United Kingdom); Erdan Gu, Univ. of Strathclyde (United Kingdom); Jason M. Smith, Univ. of Oxford (United Kingdom)

Recent demonstrations of entanglement between two remote Nitrogen-Vacancy centers, have opened the way for their use in distributed quantum networks. An efficient spin-photon interface will now be required to help realize this system as a technology.

Here we demonstrate the tunable enhancement of the zero phonon line of a single nitrogen-vacancy colour centre in nanodiamond at cryogenic temperatures. A plano-hemispherical open cavity, fabricated using focused ion beam milling provides mode volumes as small as 1.25 cubic microns and quality factor Q ~ 3000. It will be shown how the open geometry and independently adjustable mirrors allows for precise placement of the emitter in the centre of the cavity mode, and crucially enables in-situ tuning of the cavity resonances. At optimal coupling, the signal from individual zero phonon line transitions is enhanced by a factor of 6.25 through the Purcell effect and the overall emission rate of the NV- centre is increased by 40% compared with that measured from the same centre in the absence of cavity field confinement. This Purcell enhancement is mapped out as a function of cavity mode volume.

These results represent a proof of principle for a tunable cryogenic spin-photon interface. However by far the best NV optical and spin coherences are to be found in bulk material and efforts towards the production of diamond membranes are currently being made, with dimensions suitable for open-cavity coupling. Efforts towards this and preliminary results will also be discussed.

10118-33, Session 9

Plasmonics and sensing beyond classical limits *(Invited Paper)*

Mark Tame, Univ. of KwaZulu-Natal (South Africa)

Photonic sensors have applications in a range of settings, from measuring mechanical pressure in manufacturing to detecting protein concentration in biomedicine. Many sensing approaches exist, and plasmonic systems in particular have received much attention due to their ability to confine light below the diffraction limit, greatly enhancing sensitivity. Recently, quantum techniques have been identified that can outperform classical sensing methods and achieve sensitivity below the shot-noise limit. The use of quantum techniques in plasmonics for further improving sensing is currently being explored. I will present recent work on the sensing performance of a plasmonic interferometer that exploits the quantum nature of light and its high field confinement. It will be shown that, despite the presence of loss, specialised quantum resources can provide improved sensitivity and resolution beyond the shot-noise limit in compact plasmonic devices operating below the diffraction limit.

10118-34, Session 9

Practical quantum sensing at ultra trace levels with squeezed states of light *(Invited Paper)*

Raphael C. Pooser, Oak Ridge National Lab. (United States)

Quantum sensors are devices that exploit quantum mechanical effects to obtain enhanced sensitivity over their classical counterparts. Sensors that exploit quantum noise reduction, or squeezed light, have seen renewed interest in recent years as a growing number of devices that utilize optical readout – from gravitational wave detection to ultra-trace plasmonic sensing at the nanoscale – have approached their absolute limits of detection as defined by the Heisenberg uncertainty principle. At this limit, the noise is dominated by the quantum statistics of light (the shot noise limit when coherent light is used). Simultaneously, many devices, including nanoscale sensors, have reached tolerance thresholds in which power in the readout field can no longer be increased. Beyond these limits, squeezed light is required in order to further improve sensitivity in these platforms. Here, we present our work geared towards producing practical, ubiquitous quantum sensors that break through the shot noise limit to achieve state of the art sensitivities beyond the capabilities of classical devices. We demonstrate atomic magnetometers, atomic force microscopes, compressive imaging, quantum plasmonic imaging, and ultra-trace quantum plasmonic sensors with state of the art quantum noise levels well below the shot noise limit. In particular, we will outline plasmonic ultra trace sensing in a ubiquitous, off-the-shelf configuration enhanced with squeezed light in order to beat the state of the art achieved in the analogous classical sensor. This device represents our end goal of pushing quantum sensing far into the realm of practicality in a highly accessible format for the first time.

10118-35, Session 9

Approaching the Heisenberg limit without single-particle detection *(Invited Paper)*

Emily Davis, Gregory Bentsen, Monika H. Schleier-Smith, Stanford Univ. (United States)

We propose an approach to quantum phase estimation that can attain precision near the Heisenberg limit without requiring single-particle-resolved state detection. We show that the “one-axis twisting” interaction, well known for generating spin squeezing in atomic ensembles, can also amplify the output signal of an entanglement-enhanced interferometer to facilitate readout. Applying this interaction-based readout to oversqueezed, non-Gaussian states yields a Heisenberg scaling in phase sensitivity, which persists in the presence of detection noise as large as the quantum projection noise of an unentangled ensemble. Even in dissipative implementations—e.g., employing light-mediated interactions in an optical cavity or Rydberg dressing—the method significantly relaxes the detection resolution required for spectroscopy beyond the standard quantum limit.

10118-36, Session 9

Fortifying super-sensitive quantum states against decoherence using an ancillary degree of freedom

Walker D. Larson, Bahaa E. A. Saleh, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

It is well-known that the super-sensitivity of phase estimation in two-photon interferometery is diminished by the effect of decoherence. Specific to the paradigm of local phase estimation, any presence of decoherence removes all sensitivity to small shifts in the neighborhood of certain phases. For estimates of the phase difference between two arms of an interferometer using two-photon coincidence measurements, all sensitivity is lost for phase differences in the neighborhood of $\varpi/2$. The benefit of employing an ancillary optical degree of freedom alongside the principal interfering degree of freedom was recently found to fortify super-sensing two-photon states against the debilitating effect of spectral distinguishability: an effect that reduces the visibility of two-photon interference.

In the present work, we investigate the use of an ancillary degree of freedom when measuring a phase shift by use of a two-photon Mach-Zehnder-interferometer contaminated by a depolarizing channel causing decoherence: an effect that reduces both two-photon and single-photon interference visibility. We model our input state as single photons entering both input ports of an interferometer. The principal interferometer-path modes are coupled to polarization, and decoherence is modeled by replacing the density matrix describing this input with a maximally mixed state with some probability p. We calculate the sensitivity through the quantum fisher information, finding that the process of fortifying input states retains sensing at or above the standard quantum limit in the neighborhood of phase differences around $\varpi/2$, for all probabilities below 1/4 — an advantage impossible without employing the ancillary degree of freedom.

Monday - Thursday 30–2 February 2017

Part of Proceedings of SPIE Vol. 10119 Slow Light, Fast Light, and Opto-Atomic Precision Metrology X

10119-1, Session 1

Cold-atoms: A clean system for clocks based on coherent population trapping *(Invited Paper)*

Elizabeth A. Donley, Xiaochi Liu, National Institute of Standards and Technology (United States); Eugene N. Ivanov, The Univ. of Western Australia (Australia); Valeriy I. Yudin, Novosibirsk State Univ. (Russian Federation); John E. Kitching, National Institute of Standards and Technology (United States)

A review of a cold-atom clock based on coherent population trapping that highlights recent progress will be presented. Improvements in the coherence of the interrogation spectrum have resulted in the generation of dark states in the cold Rb atoms with essentially 100 % transmission – evidence that decoherence in this system is negligible. This improvement in coherence has resulted in improved short-term stability at the level of 1.5E-11 fractional frequency stability for a one second integration period. In combination with improved interrogation schemes, the improved spectrum has also resulted in dramatically smaller light shifts and improved long-term frequency stability – with the clock averaging down to the level of 1E-13 fractional frequency stability on time scales of over 10,000 seconds.

10119-2, Session 1

long coherence times with optically trapped ultra-cold atoms *(Invited Paper)*

Nir Davidson, Gadi Afek, Weizmann Institute of Science (Israel)

We study theoretically and experimentally the coherent dynamics of trapped ultra-cold atoms at high densities. A closed form expression for the spectral line shape is derived for discrete fluctuations in terms of the bare spectrum and the Poisson rate constant of collisions, which deviates from the canonical stochastic theory of Kubo [1] and can measure the kernel of velocity changing collisions [2]. We measure a prolongation of the coherence times of optically trapped rubidium atoms as their density increases, a phenomenon we call collisional narrowing in analog to the well-known motional narrowing effect in NMR [3]. We explain under what circumstances collisional narrowing can be transformed into collisional broadening [4].

On account of collisions, conventional echo techniques fail to suppress this dephasing, and multi-pulse dynamical decoupling sequences are required. We demonstrate a 20-fold increase of the coherence time with a sequence of >200 ϖ pulses [5]. We perform quantum process tomography and demonstrate an atomic memory with coherence times exceeding 3 sec. Further optimization requires utilizing specific features of the collisional bath [6] and control noise [7], which we measure directly. Finally, the spectral system can be mapped on real space anomalous diffusion [8] and optical coherence [9] problems.

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10119-3, Session 1

Chip-scale MOT for microsystems technology *(Invited Paper)*

Argyrios Dellis, John E. Kitching, National Institute of Standards and Technology (United States)

Magneto-optical traps (MOT) are the first stage for a plethora of cold atoms instruments and sensors. The miniaturization of instruments and sensors based on laser-cooled atoms is hindered by the large pumps needed to maintain the vacuum requirements (<10^-6 Torr). Currently all the laser cooled atom systems require some kind of actively pumping in order to operate. We are developing a micro-fabricated platform to support the creation of laser cooled samples for chip-scale instruments. Our chip scale cell is 4 mm thick and 28mm x 28mm wide, is made by anodically bonding glass windows to a silicon frame and is pumped by a 2 L/sec ion pump. Six independent laser beams, each having ~1mW power, and a pair anti-Helmholtz coils are used to cool and trap ~ 1million atoms. We have characterized the MOT system and we are in the process of replacing the actively pumped cell by a passively pumped cell where the pumping elements are non-evaporable getters.

10119-4, Session 2

New method for enhancement of contrast of coherent population trapping resonance in Rb vapour

Sergey M. Kobtsev, Daba A. Radnatarov, Sergey A. Khripunov, Ivan Popkov, Valerii Andryushkov, Novosibirsk State Univ. (Russian Federation); Tatiana Steschenko, Vladimir Lunin, Yurii Zarudnev, Novosibirsk State Univ (Russian Federation)

This work presents a new method of contrast enhancement for coherent population trapping resonance (CPT) consisting in stabilisation of the value of a function related to pump radiation absorption at the D1 absorption line in a 87Rb vapour cell by adjusting the pump radiation intensity via a feed-back loop. The coherent population trapping resonance in this method is created as the dependence of the transmitted pump radiation intensity upon the frequency difference of the bi-chromatic pump field. Absorption of the pumping field within the cell is registered with two photo-detectors measuring the radiation power prior to and after the cell. The input pumping power is controlled with an electro-optical modulator. The inner walls of the experimental rubidium vapour cell have an anti-relaxation coating. For relatively slow scanning of the CPT resonance (scanning frequency of the frequency difference of the bi-chromatic field ≤ 1 Hz), the proposed method resulted in resonance contrast (ratio of its height to the base-line transmission) enhancement over two orders of magnitude, from 1% to 108%. For dynamically excited CPT resonances (scanning frequency of the frequency difference of the bi-chromatic field of > 100 Hz), the corresponding CPT resonance contrast enhancement was by a factor of several tens. The present work provides details of the proposed method and its comparison with other ways to enhance CPT resonance contrast. Simpler technical requirements of the proposed method of CPT resonance contrast enhancement opens up new possibilities for application of resonances of this type in metrological applications.

10119-5, Session 2

Nanophotonic tools for metrology: photonically-integrated atomic vapor cells and octave-spanning microresonator frequency combs *(Invited Paper)*

Kartik Srinivasan, National Institute of Standards and Technology (United States)

No Abstract Available

10119-6, Session 2

Stabilization and line narrowing of a frequency comb locked to an acetylene stabilized fibre laser

Thomas Talvard, Danish Fundamental Metrology (Denmark); Nicolai F. Mortensen, Aarhus Univ. (Denmark); Bjarke Gøth, NKT Photonics A/S (Denmark); Philip G. Westergaard, Danish Fundamental Metrology Institut (Denmark); Michael V. DePalatis, Michael Drewsen, Aarhus Univ. (Denmark); Jan Hald, Danish Fundamental Metrology Institut (Denmark)

We demonstrate a significant improvement when referencing a frequency comb to an acetylene stabilized fiber laser as compared to a GPS-disciplined Rb clock reference. The Stabilaser 1542 is a compact, maintenance-free stand-alone acetylene stabilized fiber laser with a narrow linewidth and an Allan deviation of 3E-13 and 4E-14 in 1 s and 10000 s, respectively. Switching the comb reference from the Rb clock to the Stabilaser 1542 improves both comb linewidth and Allan deviation by about two orders of magnitude. Furthermore, long-term measurements of the Stabilaser 1542 frequency with reference to the GPS-disciplined clock indicate a potential accuracy of 1E-12.

10119-7, Session 2

Analytical Tools for Point Source Interferometry

Gregory W. Hoth, Bruno Pelle, John E. Kitching, Elizabeth A. Donley, National Institute of Standards and Technology (United States)

Most atom interferometer gyroscopes require two counter-propagating atomic sources to distinguish the phase shifts due to rotations and accelerations. We present an atom interferometer that can simultaneously measure two rotation components and one acceleration component with a single cloud of atoms. In our set up, this simplification is achieved by extending the point-source interferometry technique (Dickerson et al. PRL, 111, 083001, 2013).

In point source interferometry, counter-propagating atoms are obtained with a single cloud by exploiting the thermal velocity distribution. During the measurement, the cloud expands which means each atom's final position is correlated with its initial velocity. The velocity-dependent rotation phase shift manifests as a spatial fringe that can be detected by imaging the cloud. The orientation and spacing of the fringe pattern corresponds to the direction and magnitude of the rotation rate. The overall phase of the fringe pattern corresponds to the acceleration.

In the point source limit where the initial cloud is infinitesimally small, the correlation between an atom's initial velocity and its final position is perfect. However, in a real device, the cloud will have a finite initial size. We show both experimentally and theoretically that the details of the initial phase space distribution will alter the spatial fringes, shift the scale factor of the measurement, and constrain the dynamic range of a gyroscope based on this technique. Despite these complications, it appears to be possible to realize a point-source interferometry gyroscope that achieves performance levels of interest for applications.

10119-8, Session 3

The first observation of superradiant emission on a millihertz linewidth optical transition in strontium *(Invited Paper)*

David Auerbach, James Thompson, JILA (United States)

No Abstract Available

10119-9, Session 3

Airborne and underground tests of general relativity with cold atoms *(Invited Paper)*

Philippe Bouyer, Lab. Photonique, Numérique et Nanosciences (France)

No Abstract Available

10119-11, Session 4

Sensors enhanced by quantum effects: current challenges and prospects from the AFOSR perspective *(Invited Paper)*

Tatjana Curcic, Air Force Office of Scientific Research (United States)

Over the past two decades, we have witnessed remarkable scientific advances in the broad area of quantum information science (QIS). Quantum sensing has emerged as a distinct and burgeoning branch of QIS with opportunities to fundamentally transform our measurement capabilities, enabling higher sensitivity and precision in a number of applications that are of interest to the Air Force. Recent advances in, for example, the ability to control individual quantum objects, or to create strong squeezing, bring quantum sensors closer to becoming a viable technology. I will present examples of AFOSR-supported research in the area of quantum sensing, discuss current challenges and future outlook.

10119-12, Session 4

Ultra-high Compton frequency, parity independent, mesoscopic Schrödinger cat atom interferometer with Heisenberg limited sensitivity *(Invited Paper)*

Resham Sarkar, Minchuan Zhou, Renpeng Fang, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

10119-13, Session 4

0.75 atoms improve the clock signal of 10,000 atoms

Wolfgang A. Ertmer, Ilka Kruse, Karsten Lange, Jan Peise, Bernd Lücke, Leibniz Univ. Hannover (Germany); Luca Pezze, Augusto Smerzi, Lab. Europeo di Spettroscopie Non-Lineari (Italy); Jan J. Arlt, Aarhus Univ. (Denmark); Christian Lisdat, Physikalisch-Technische Bundesanstalt (Germany); Luis Santos, Carsten Klempt, Leibniz Univ. Hannover (Germany)

Since the pioneering work of Ramsey, atom interferometers are employed for precision metrology, in particular to measure time and to realize the second. In a classical interferometer, an ensemble of atoms is prepared in one of the two input states, whereas the second one is left empty. In this case, the vacuum noise restricts the precision of the interferometer to the standard quantum limit (SQL). Here, we propose and experimentally demonstrate a novel clock configuration that surpasses the SQL by squeezing the vacuum in the empty input state. We create a squeezed vacuum state containing an average of 0.75 atoms to improve the clock sensitivity of 10,000 atoms by 2.05 dB. The SQL poses a significant limitation for today's microwave fountain clocks, which serve as the main time reference. We evaluate the major technical limitations and challenges for devising a next generation of fountain clocks based on atomic squeezed vacuum.

10119-14, Session 5

Slow and fast light via two-wave mixing in the rare-earth doped optical fibers *(Invited Paper)*

Serguei I. Stepanov, Marcos Plata Sánchez, Eliseo Hernández, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico)

Dynamic population Bragg gratings can be recorded in the rare-earth-doped (e.g. doped with erbium or ytterbium) optical fibers with mWatt-scale cw laser power. Two-wave mixing (TWM) via such gratings is utilized in single-frequency fiber lasers and in adaptive interferometric fiber sensors with automatic stabilization of the operation point. Slow and fast light propagation can also be observed in the vicinity of narrow (~20-200Hz) spectral profile of stationary no-degenerate TWM. In particular, slow light propagation is observed for the purely amplitude grating, recorded in the erbium-doped fiber in spectral range 1510-1550nm. In its turn, in ytterbium-doped fibers at 1064nm (or in erbium-doped fiber at the wavelength below 1500nm) the dynamic grating has significant contribution of the phase component, the TWM profile has essentially asymmetric form, and both slow and fast (superluminal) light propagation is possible at different frequency off-sets between the counter-propagating interacting waves.

10119-15, Session 5

Parametric interaction of slow light and sound in a bottle resonator *(Invited Paper)*

Misha Sumetsky, Aston Univ. (United Kingdom)

No Abstract Available

10119-16, Session 5

Perforated hollow-core optical waveguides for chip-scale spectroscopy and quantum interference *(Invited Paper)*

Matthieu Giraud-Carrier, Brigham Young Univ. (United States); Jennifer A Black, Holger Schmidt, Univ. of California, Santa Cruz (United States); Aaron R. Hawkins, Brigham Young Univ. (United States)

No Abstract Available

10119-17, Session 5

Transient quantum coherent effects in the acetylene-filled hollow-core photonic crystal fiber

Serguei I. Stepanov, Nayeli Casillas-Rodriguez, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico); Manuel I. Ocegueda Miramontes, Univ. Autónoma de Baja California (Mexico); Eliseo Hernández, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico)

Low-pressure acetylene in the hollow-core photonic crystal structure fibers is an excellent object for room-temperature observation and investigation of coherent quantum effects in the communication wavelength region around 1530nm. During recent decade some stationary effects and configurations like saturation absorption spectroscopy and electromagnetically induced transparency (EIT) were investigated. The pulsed light excitation leads to observation of new transient coherent phenomena and also enables evaluation of important temporal characteristics of the light-molecule interactions. Recently [1] we have reported observation of very efficient optical nutation oscillations and photon echo, which has also ensured direct evaluation of the Rabi oscillation frequency and of the transverse relaxation time.

In this presentation we also report original results on observation of the transient EIT excitation both in the co- and counter-propagation geometries for V and for ? interaction configurations. Experiments were performed with an all-fiber acetylene-filled cell in the gas pressure range 200-400mTorr, utilizing semiconductor DFB lasers tunable around 1520 and 1530nm with the nanosecond-long control pulses of the Watt-scale maximum power. Simple theoretical model of the spatially non-uniform EIT, based on consideration of the moving acetylene molecule interaction with the interference pattern formed by the control and the probe coherent waves, was used to explain the difference in the efficiency of the effect observed for co- and counter-propagating waves. Experimentally observed distributions of the EIT efficiency across the Doppler-broadened acetylene absorption lines between these configurations are also reported and explained within the framework of the above-mentioned theoretical model.

[1] M. Osegueda et al. Phys.Rev.A 89, 063403 (2014).

10119-18, Session 5

Possibility of femtosecond soliton mode propagation with complicated pulse chirp

Vyacheslav A. Trofimov, Tatiana M. Lysak, M.V. Lomonosov Moscow SU (Russian Federation)

We predict a new type of fast chirped soliton at a femtosecond pulse propagation in a medium containing the noble nanoparticles. This soliton type is characterized by the complicated pulse chirp. At our analysis we take

into account the TPA of laser radiation by nanorods, and time-dependent nanorod aspect ratio changing due to their reshaping because of laser energy absorption. The chirped soliton is formed due to the trapping of laser radiation by the nanorods reshaping front, if a positive or negative phase-amplitude grating is induced by laser radiation. We analyze the conditions for the soliton with complicated chirp occurrence.

10119-19, Session 6

Slow light and fast light: a tutorial review *(Invited Paper)*

Robert W. Boyd, Institute of Optics, Univ. of Rochester (United States)

This presentation will begin with a brief review of the physics of slow and fast light, and will include a brief history of the development of this field. The talk will then move on to a discussion of some recent work aimed at the development of applications of slow light. We will review the use of slow light in the fabrication of miniature spectrometers and for accurate measurements of velocity based on the photon drag effect.

10119-21, Session 7

Controlling group delay with passive and active microresonators *(Invited Paper)*

Takashi Yamamoto, Motoki Asano, Osaka Univ. (Japan); Sahin Ozdemir, Washington Univ. in St. Louis (United States)

Slow and fast light phenomena in solid state material were observed in many different physical systems having a resonant transmission, such as microcavity, an array of directly coupled microcavities, and photonic crystals. Tunable control of slow and fast light has been implemented using nonlinear optical gain, such as Raman and Brillouin gain, to realize tunable delay lines in integrated photonic systems. In the case of whispering-gallery-mode (WGM) microresonators, the tunability has been provided by controlling the coupling strength between a microcavity and a waveguide by changing the gap between them. In this talk, we present an alternative method giving the tunability with a gain medium, which enables the tuning without changing the gap and loss compensation. In addition, we will report anomalous time delay and quantum weak measurements in a waveguide-coupled microresonator.

10119-22, Session 7

Superluminal and slow light in eye-like ring resonator

Yundong Zhang, Harbin Institute of Technology (China)

We investigate the phase and group delay in eye-like ring resonator with the effect of different coupling coefficients and attenuation factors. The eye-like structure is composed of two bus waveguides coupling with the outer ring and the two rings coupling together which have different perimeters. The eye-like ring resonator has two outputs which have different transmission characteristics. In this paper, we measure the group delay of the two outputs through changing the coupling coefficients and the attenuation factors of the inner and the outer ring. The result shows that the two outputs have reverse group delay(superluminal and slow light) which will have potential use in slow light fiber, optical buffers and optical switches.

10119-23, Session 7

Theoretical analyses of the effect of dispersion on optical cavity *(Invited Paper)*

Jian Lin, Hao Zhang, Wenxiu Li, Junjie Jin, Jiaming Liu, Xiaofu Zhang, Anping Huang, Zhisong Xiao, BeiHang Univ. (China)

No Abstract Available

10119-24, Session 7

Tunable fast and slow light based on ring resonators and Mach-Zehnder interferometer *(Invited Paper)*

Yundong Zhang, Harbin Institute of Technology (China)

We theoretically investigate the dispersion transition between abnormal dispersion and normal dispersion in a coupled ring resonator. The transfer function of two outputs in ring resonator coupled Mach–Zehnder interferometer are expressed by transfer matrix theory. The results of changing coupling coefficients from the undercoupled regime to the overcoupled regime will lead to the transition from fast light to slow light. The simulation results show that changing the coupling coefficients has a significant affection to the tunable group delay. The coupled ring resonator with the tunable dispersion (group delay) can exploited for optical storage devices, slow light Fourier transform (FT) interferometric spectrometers, optical switches, optical routers, and optical sensors.

10119-55, Session 7

Unconventional photonic crystals, chaos, and rogue waves *(Invited Paper)*

Thomas F. Krauss, Univ. of York (United Kingdom)

No Abstract Available

10119-25, Session 8

Biphoton generation in the group-delay regime *(Invited Paper)*

Shengwang Du, Hong Kong Univ. of Science and Technology (Hong Kong, China)

No Abstract Available

10119-26, Session 8

Applications of four-wave mixing to quantum information *(Invited Paper)*

Alexander L. Gaeta, Columbia Univ. (United States)

No Abstract Available

10119-27, Session 8

Design of periodic waveguide for enhancing the interaction of light and atoms in a vacuum *(Invited Paper)*

Philippe Lalanne, Xiaorun Zang, Rémi Faggiani, Institut d'Optique d'Aquitaine (France); Jianji Yang, Institut d'Optique d'Aquitaine (France)

The emerging field of on-chip integration of nanophotonic devices and cold atoms offers extremely-strong and pure light-matter interaction schemes, which may have profound impact on quantum information science. In this context, a long-standing obstacle is to achieve strong interaction between single atoms and single photons, while at the same time trap atoms in vacuum at large separation distances from dielectric surfaces. In this design work, with advanced photonic crystal software [Opt. Lett. 40, 3869 (2015)], we study new photonic-crystal waveguide geometries that offer a good compromise, which additionally allow for easy manipulation of atomic clouds around the structure. At the conference, we will present extension of our work recently published [Phys. Rev. Appl. 5, 024003(2016)].

10119-28, Session 8

Theory of few-photon quantum scattering in nanophotonic structures *(Invited Paper)*

Shanshan Xu, Shanhui Fan, Stanford Univ. (United States)

The capability to create strong photon-photon interaction at a few-photon level in integrated photonic systems is of central importance for quantum information processing. To achieve such a capability, an important approach is to confine photons in a one-dimensional waveguide that is coupled to a quantum multi-level system. At a fundamental level, photon-photon interaction in such system is described by multi-photon scattering matrix. We present the general structure of such scattering matrix from the cluster decomposition principle in quantum field theory. We also extend the input-output formalism of quantum optics that provides an analytic tool to compute multi-photon scattering matrix systematically.

10119-30, Session 8

Coupled-mode equations for heterogeneous photonic media with a retarded coherent response

Igor V. Melnikov, National Research Univ. of Electronic Technology (Russian Federation)

No Abstract Available

10119-36, Session 8

Nanofiber quantum photonics *(Invited Paper)*

Kohzo Hakuta, Kali Prasanna Nayak, Ramachandrarao Yalla, The Univ. of Electro-Communications (Japan)

In the last decade, tapered optical fibers with subwavelength diameter waist, known as optical nanofibers, have been widely adapted in various photonic applications. The strong transverse confinement of nanofiber guided field and its ability to interact with the surrounding medium, provides a platform for non-linear optical processes in a fiber-based system. Such interactions can be further enhanced to single quanta level by fabricating cavity structure on the nanofiber. A key aspect of such a nanofiber-based cavity is the independent control of transverse and longitudinal confinement. As a result by controlling the cavity length, one can achieve both Purcell regime and strong-coupling regime for cavity QED in a moderate finesse cavity. We will present the experimental developments on nanofiber-based cavity QED system.

10119-31, Session 9

Microfabricated optically-pumped magnetometer arrays for biomedical imaging *(Invited Paper)*

Abigail R. Perry, Univ. of Colorado Boulder (United States); Dong Sheng, University of Science and Technology of China (China); Sean Krzyzewski, Shawn Geller, Svenja A. Knappe, Univ. of Colorado Boulder (United States)

Atomic magnetometers have demonstrated magnetic field measurements as precise as the best superconducting magnetometers. Our group develops miniature magnetic sensors using microfabrication technology. Our sensors do not require cryogenic cooling, and are relatively low cost, making these sensors an attractive option for development in the medical community. We will present our latest chip-scale atomic gradiometer developed for array applications to image magnetic fields from the brain noninvasively. These developments should lead to improved spatial resolution, and sensitive measurements in unshielded environments.

10119-32, Session 9

Precision magentometry with NV-diamond *(Invited Paper)*

Danielle A. Braje, MIT Lincoln Lab. (United States)

No Abstract Available

10119-33, Session 9

Resonant and level anti-crossing magnetometry with color centers in diamond *(Invited Paper)*

Huijie Zheng, Georgios Chatzidrosos, Arne Wickenbrock, Lykourgos Bougas, Johannes-Gutenberg University Mainz (Germany); Reinis Lazda, Florian H Gahbauer, Andris Berzins, Ruvins Ferbers, Marcis Auzins, The University of Latvia (Latvia); Dmitry Budker, Johannes Gutenberg Univ. Mainz (Germany)

No Abstract Available

10119-34, Session 9

Toward custom design of diamond-based quantum sensors *(Invited Paper)*

Philip R. Hemmer, Texas A&M Univ (United States)

I discuss new ways to grow diamond that promise near-deterministic design of fluorescent color-centers, optimized for quantum sensing applications. Briefly diamonds are grown around diamond-like organic seed molecules that have the dopant atoms needed for specific color centers, located in the correct approximate locations. It can be seen that this approach can give unprecedented control over the number and placement of color

centers. Complete quantum registers might also be fabricated, for example a nitrogen-vacancy and at 13C atom with a well-defined separation surrounded by only 12C diamond. In this talk I will discuss our first key success, which is growing diamonds under conditions where the seed molecules are stable, as well as current experiments.

10119-35, Session 9

Measurement of magnetic field gradients using atom interferometers *(Invited Paper)*

Frank A. Narducci, Naval Air Systems Command (United States)

No Abstract Available

10119-38, Session 10

Tailoring speed of light in heterogeneous photonic crystal via inverse Faraday effect *(Invited Paper)*

Igor V. Melnikov, National Research Univ. of Electronic Technology (Russian Federation)

No Abstract Available

10119-66, Session 10

Epsilon near zero materials: yet another slow light scheme *(Invited Paper)*

Jacob B. Khurgin, Johns Hopkins Univ. (United States)

Recent years have seen increased interest to the artificial media with very low dielectric permittivity, the so-called “epsilon near zero” (ENZ) materials. These materials have been shown to have interesting linear and nonlinear optical properties and as such have revived the hopes for future efficient all-optical device operating at low powers. This situation is similar to the one surrounding slow light media a few years ago and indeed all the ENZ schemes are characterized by extremely low group velocity. In this talk I will show that all the properties of the ENZ materials can be explained by their scaling with low group velocity, and their figures of merit and limitations (bandwidth and loss) are the same as those in slow light or other resonant schemes. I will also explain the consequences for practical optical devices.

10119-39, Session 11

Realization of the GEIT process in an optomechanical cavity for enhancing the sensitivity-bandwidth product in a gravitational-wave detector

Minchuan Zhou, Selim M. Shahriar, Northwestern Univ. (United States); Seunghwi Kim, Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)

No Abstract Available

10119-40, Session 11

Slow light in an optomechanical microresonator system *(Invited Paper)*

Albert T. Rosenberger, Oklahoma State Univ. (United States)

Acoustic whispering-gallery modes (WGMs) in a fused-silica microresonator can be excited by forward stimulated Brillouin scattering when the acoustic frequency equals the difference in frequency between two optical WGMs. This optomechanical interaction, which is nonlinear, has a threshold, and must be phase-matched, can then affect other processes, such as optical pulse delay or advancement, i.e., slow or fast light. Several different cases are considered here, including: frequency-degenerate optical WGMs, showing induced transparency or induced absorption; frequency-separated optical WGMs, with single-mode delay or advancement; and orthogonally polarized optical WGMs, in various configurations.

10119-41, Session 11

Nonreciprocal slow and fast light with whispering gallery optomechanics *(Invited Paper)*

Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)

No Abstract Available

10119-42, Session 11

Ultra-sensitive force detection with optically trapped nanospheres *(Invited Paper)*

Andrew Geraci, Univ. of Nevada, Reno (United States)

In high vacuum, optically-trapped dielectric nanospheres achieve excellent decoupling from their environment and experience minimal friction, making them ideal for precision force sensing. We have shown that 300 nm silica spheres can be used for calibrated zeptonewton force measurements in a standing-wave optical trap. In this optical potential, the known spacing of the standing wave anti-nodes can serve as an independent calibration tool for the displacement spectrum of the trapped particle. I will describe our progress towards using these sensors for tests of the Newtonian gravitational inverse square law at micron length scales. Optically levitated dielectric objects also show promise for a variety of other precision sensing applications, including searches for gravitational waves and other experiments in quantum optomechanics.

10119-43, Session 12

Raman ring lasers using Rb vapor for precision metrology

Joshua Yablon, Zifan Zhou, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

10119-44, Session 12

Increased resolving power in a slow-light multibeam interferometer *(Invited Paper)*

David D. Smith, NASA Marshall Space Flight Ctr. (United States)

No Abstract Available

10119-45, Session 12

Thermal self-stability, multi-stability, and memory effects in Brillouin fiber lasers *(Invited Paper)*

Omer Kotlicki, Jacob Scheuer, Tel Aviv Univ. (Israel)

No Abstract Available

10119-46, Session 12

Observation of thermodynamic phase noise using a slow-light resonance in a fiber Bragg grating *(Invited Paper)*

Michel J. F. Digonnet, George Skolianos, Arushi Arora, Stanford Univ. (United States); Martin Bernier, Univ. Laval (Canada)

No Abstract Available

10119-47, Session 12

Slow-light enhanced performance of chip-scale silicon photonic spectral-measurement devices

Shayan Mookherjea, Univ. of California, San Diego (United States)

No Abstract Available

10119-48, Session 12

Controlling the group delay and phase of fs pulses with liquid crystals for spectroscopy and hyperspectral imaging *(Invited Paper)*

Aurelie Jullien, Umberto Bortolozzo, Stefania Residori, Institut Non Linéaire de Nice Sophia Antipolis (France); Stephanie Grabielle, Nicolas Forget, FASTLITE (France); Jean-Pierre Huignard, JPHopto (France)

We introduce a new device for group and phase delay steering of femtosecond pulse trains that makes use of cascaded, electrically driven, nematic liquid-crystal cells. Based on this approach we demonstrate a continuously tunable optical delay line. The simple collinear implementation with no moving parts enables to shape the achievable temporal range with sub-femtosecond accuracy. By appropriately choosing the bias voltages applied to the cascaded cells, the imparted group delay can be made either positive or negative and precisely adjusted. Moreover, independent control of the group delay and the phase of femtosecond pulses is demonstrated. The presented results disclose an innovative approach in the manipulation of femtosecond pulse trains for phase control or pump-probe spectroscopy. Finally, application to liquid crystal based Fourier transform spectrometer and high resolution hyperspectral imaging is demonstrated.

10119-49, Session 13

Magnetic resonance spectroscopy on a diamond chip *(Invited Paper)*

Victor M. Acosta, The Univ. of New Mexico (United States)

Our lab is developing a diamond-chip-based platform for determining composition, structure, and function of trace biochemical analytes via nuclear magnetic resonance (NMR), nuclear quadrupole resonance (NQR), and electron paramagnetic resonance (EPR) spectroscopies. The platform consists of a nanostructured diamond chip doped with Nitrogen-Vacancy (NV) color centers and uses non-inductive optical detection and high-aspect-ratio nanogratings to enhance sensitivity in a wide range of magnetic fields and at ambient temperature. We have recently demonstrated solution-state NMR, NQR detection of thin films, and EPR detection of external spins with this platform.

10119-50, Session 13

Towards nanophotonic devices based on slow light in rare-earth-doped media and their applications *(Invited Paper)*

Jonathan M. Kindem, Tian Zhong, John G. Bartholomew, Andrei Faraon, California Institute of Technology (United States); Byoung S. Ham, Gwangju Institute of Science and Technology (Korea, Republic of)

No Abstract Available

10119-51, Session 13

Emitters in dispersive nanostructures *(Invited Paper)*

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

No Abstract Available

10119-52, Session 13

Chip scale light platforms for metrology, frequency stabilization, and enhanced-light matter interactions *(Invited Paper)*

Liron Stern, Meir Grajower, Jonathan Bar David, Roy Zektzer, Alex Naiman, Noa Mazurski, Uriel Levy, The Hebrew Univ. of Jerusalem (Israel)

No Abstract Available

10119-53, Session 13

Slow-light-enhanced graphene photonics *(Invited Paper)*

N. Asger Mortensen, DTU Fotonik (Denmark)

No Abstract Available

10119-20, Session 14

The role of slow light on disorder-induced losses in laser cavities *(Invited Paper)*

Jesper Mork, Yi Yu, Elizaveta Semenova, Kresten Yvind, Technical Univ. of Denmark (Denmark)

In the talk we will discuss the role of disorder-induced losses on the threshold of line-defect photonic crystal lasers. Experiments reveal an optimum cavity length, on the order of 10 unit cells, where the laser threshold density attains a minimum. The results can be explained by considering the role of slow-light propagation on the threshold of a photonic crystal laser. We will also discuss the possibility of alleviating this dependence on cavity length by replacing one of the mirrors with a narrow-band mirror based on a Fano resonance.

10119-54, Session 14

Control of light through photonic crystal unit cell design *(Invited Paper)*

Sharon M. Weiss, Vanderbilt Univ. (United States)

No Abstract Available

10119-59, Session 14

Optical delays to achieve optical signal processing functions *(Invited Paper)*

Alan E. Willner, The Univ. of Southern California (United States)

Multiplexing of multiple coherent beams can produce different signal processing functions, and operating on the amplitude and phase simultaneously can multiply processing capacity. Moreover, tunable optical delays can help achieve these functions reconfigurably. Using mixing in nonlinear elements, this paper will discuss optical signal processing functions, with emphasis on regeneration, correlation, filter shaping, and crosstalk mitigation.

10119-56, Session 15

Advanced slow-light modulators *(Invited Paper)*

Toshihiko Baba, Yokohama National Univ. (Japan)

Slow light in photonic crystal waveguides allows the phase shifters in Si MZ modulators to enhance the modulator efficiency. In this study, the group index and bandwidth product is maximized, the mode penetration into photonic crystal claddings and electrical series resistance are balanced, and the p-n junction profile is optimized. The device is fabricated on 200 mm wafer using KrF exposure, and practical performance (bitrates up to 32 Gbps, 3 dB extinction ratio, 1.75 V PPG voltage, <0.2 pJ/bit energy consumption, 20 nm bandwidth, 5 dB passive loss, 1 dB modulation loss) is obtained in a 200-micron device. WDM, QPSK, PAM and sub-bandgap PD operations are also demonstrated.

10119-57, Session 15

Compact high-speed photonic crystal electro-optics modulators *(Invited Paper)*

Bruce W. Wessels, Northwestern Univ. (United States)

We report on the on a photonic crystal (PhC) optical modulator operating in the optical C band (1530-1565 nm). The platform is $BaTiO_3$, a ferroelectric with a very large electro-optic coefficient. At microwave frequencies from 10 to 45 GHz enhancement of the electro-optic coefficient is observed due to slow light effects. A monotonic increase of the effective electro-optic coefficient from 60 to 110 pm/V is observed across the stop band edge, resulting in an enhancement as high as 1.8. The enhancement enables fabrication of modulators with electrode lengths of the order of one millimeter. Utilization of these devices in photonic integrated circuits (PICs) for coherent optical communication systems is envisioned.

10119-58, Session 15

Dynamical holography and wavefront control with liquid-crystal light valve *(Invited Paper)*

Stefania Residori, Umberto Bortolozzo, Institut Non Linéaire de Nice Sophia Antipolis (France); Daniel Dolfi, Pascale Nouchi, Thales Research & Technology (France); J. P. Huignard, Jphopto (France); Stephanie Molin, Thales Research & Technology (France); Arnaud Peigné, Thales Underwater Systems (France)

Dynamical holography is realized with liquid crystal light valves, namely optically addressed spatial light modulators (OASLM) based on the association of a GaAs semiconductor and nematic liquid crystals. We show that the OASLM is sensitive in the near infrared and allows measuring small phase modulations in noisy environments and with distorted optical wavefronts. We realize an adaptive interferometer for distributed acoustic sensing, which is based on adaptive holography in an OASLM coupled with a multimode optical fiber as sensing element. The holographic interferometer is, then, combined with a detection method based on Phase-Optical Time Domain Reflectometry. Because of the OASLM finite response time, the hologram is self-adapted to low frequency phase variations and the interferometer does not require stabilization. Thanks to this property, the system can operate with multimode optical beams, which allows improving the single to noise ratio of the transducer sensing element.

10119-60, Session 16

A velocity sensor based on large Fizeau's light dragging effect in a moving electromagnetically-induced transparent medium *(Invited Paper)*

Shau-Yu Lan, Nanyang Technological Univ. (Singapore)

Atoms based velocimeter typically relies on measuring the first order Doppler shift of individual atoms. To determine the center-of-mass motion of an atomic ensemble, one usually needs to map out or truncate the velocity distribution of the ensemble. Here, I will describe the light dragging effect in a moving electromagnetically induced transparent (EIT) medium and use it to sense the center-of-mass motion of an atomic ensemble directly. The light dragging effect or the deviation of phase velocity from

the speed of light c in a moving medium was first observed by Fizeau in a flowing water experiment for the study of ether in the pre Einstein's special theory of relativity era. It was later explained by the Lorentz velocity addition to the first order. We enhance the dragging effect in a cold atomic medium under EIT condition and demonstrate a velocity sensor at a sensitivity two orders of magnitude higher than the velocity width of the atomic medium used. This new type of sensor depends on the collective motion of the atomic ensemble and could lead to a new design of motional sensor beyond the limitation of Doppler broadening of atoms.

10119-61, Session 16

Slow light and light storage in metastable helium atoms at room temperature *(Invited Paper)*

Fabien Bretenaker, Fabienne Goldfarb, Marie-Aude Maynard, Jasleen Lugani, Etienne Brion, P. Neveu, R. Bouchez,, Lab. Aimé Cotton (France); Rupamanjari Ghosh, Jawaharlal Nehru Univ. (India)

Quantum memories are required for quantum information applications, and different protocols for storing light pulses have been investigated, such as Electromagnetically Induced Transparency (EIT) based storage, Raman storage or photon echo techniques. Though they open promising perspectives with respect to efficiency, fidelity or storage time, all these protocols rely on the excitation of an atomic coherence between two ground states and, as a consequence, are very sensitive to dephasing effects. We showed experimentally that it is possible to perform light storage using CPO in a ? system composed of two lower levels coupled to the same excited level: this new form of storage is phase preserving, with the advantage of being robust to dephasing effects such as magnetic field gradients. We also showed theoretically that light is stored into the difference of population between the 2 lower states of the 3-level system.

10119-62, Session 17

A truncated SU(1,1) interferometer for phase estimation beyond the standard quantum limit *(Invited Paper)*

Bonnie L. Schmittberger, Brian E. Anderson, Prasoon Gupta, Travis Horrom, Carla Hermann-Avigliano, Univ. of Maryland, College Park (United States); Kevin M. Jones, Williams College (United States); Paul D. Lett, National Institute of Standards and Technology (United States) and Univ. of Maryland, College Park (United States)

There has been a recent surge of interest in studying the phase-sensing ability of SU(1,1) interferometers, which replace the beamsplitters in a Mach-Zehnder interferometer with nonlinear optical processes. We present a novel phase measurement device that is similar to an SU(1,1) interferometer but uses a simpler detection scheme. We show theoretically that this "truncated SU(1,1) interferometer" achieves the same potential phase sensitivity as that of a full SU(1,1) interferometer in the case of no loss, and we compare the phase sensitivities of various detection schemes. We build a version of the truncated SU(1,1) interferometer and study its potential phase sensitivity over a range of operating points. We show that our apparatus beats the standard quantum limit by 4 dB. This device has potential applications in precision metrology, such as in biological sensing, where there is a strong interest in enhancing the phase sensitivity at low optical powers.

10119-63, Session 17

Distributed Brillouin analysis with ultra-high-resolution using amplified spontaneous emission sources *(Invited Paper)*

Yosef London, Raphael A. Cohen, H. Hagai Diamandi, Eyal Preter, Avi Zadok, Bar-Ilan Univ. (Israel)

Distributed Brillouin sensing of temperature and strain along optical fibers with spatial resolution of few millimeters is proposed and demonstrated. Unlike other setups, in which the Brillouin pump and signal waves are drawn from modulated, narrowband laser diode sources, here broadband amplified spontaneous emission is used instead. The Brillouin interaction is effectively confined to a single narrow segment, whose extent equals the coherence length of the broadband source. The point of measurement is scanned along the fiber under test using variable optical delay lines. A measurement resolution of 3 millimeters in a small-core, single-mode silica fiber is achieved experimentally. The technique is scalable to sub-millimeter resolution in distributed measurements along tapered fibers and photonic devices. It is suitable for the characterization of components used in high-power fiber lasers.

10119-64, Session 17

Method for all-optical sampling without an optical source *(Invited Paper)*

Thomas Schneider, Technische Univ. Braunschweig (Germany); Stefan Preussler, IHF (Germany)

To convert an analogue to an electrical signal a sampling of the analogue signal is required. For ideal sampling an unlimited number of equal copies of the signal spectrum is generated. Electrical sampling instead produces a limited number of copies multiplied by a sinc-function. All-optical sampling can be seen as the multiplication of the copies by a Gaussian function. Here we present a very simple method of all-optical sampling which requires neither nonlinear optics nor a mode-locked laser. Besides practical limitations, the only difference to ideal sampling is the fact that a limited number of copies is generated. The idea behind the method as well as first preliminary results for sampling rates up to 90 GSa/s are presented.

Conference 10120: Complex Light and Optical Forces XI

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10120-1, Session 1

Structuring light with dielectric metasurfaces *(Invited Paper)*

Antonio Ambrosio, Harvard Univ. (United States)

The characteristic screw-type dislocation of a helical mode can be imposed on the wave-front of a propagating beam by means of different devices like pitchfork holograms, axicons lenses or reflectors. However, helical modes can be also produced exploiting the geometrical phase, also known as Pancharatman-Berry (PB) phase. This method consists in a phase shift imposed by creating an optically inhomogeneous medium where the incident light experience transversely inhomogeneous polarization transformations corresponding to a closed path on the Poincaré sphere (space of polarization states).

We have realized devices made of dielectric sub-wavelength resonators on glass substrates designed to convert an incident Gaussian beam into a vortex beam with high-efficiency in the visible light spectrum. Similarly to Liquid-Crystals q-plates, our devices exploit the geometrical phase principle to couple the light spin momentum of the incident beam to the orbital angular momentum of the vortex beam. Our approach allows designing spin-to-orbital angular momentum converters with high values of topological charges of the vortex beam for visible light. The reproducibility of the fabrication process together with the high efficiency (>60%) have significant potential to advance research in microscopy and quantum optics.

10120-2, Session 1

Characterization of the unfolding process of an optical vortex *(Invited Paper)*

Yoko Miyamoto, Sunil Vyas, The Univ. of Electro-Communications (Japan)

When a uniformly polarized beam with an optical vortex enters a birefringent crystal, it separates into an ordinary (o) ray and an extraordinary (e) ray, each with its optical vortex. As the two vortices begin to separate in space, a highly complex polarization distribution appears that is initially localized and gradually expands to dominate the overlapping area. This phenomenon is called the “unfolding” of an optical vortex.

In this paper we introduce the concept of the “unfolding region” to characterize the unfolding process. This is the real space region over which the polarization state travels half way around the Poincare sphere relative to the polarization state observed at the midpoint between the two separating vortices. This allows us to characterize the process independently from the overall phase shift between the e-ray and o-ray.

In the case of 0 tilt between the e-ray and o-ray the region is a circle where the line segment connecting the two vortices is the diameter. A small relative tilt can be shown to distort this circle into an ellipse. We have applied the above analysis to an actual unfolding process observed with the birefringent interferometer [1], and have identified and measured the area of the unfolding region for various separations d between the two vortices. Elliptical distortion of the unfolding region was observed at small separations, which was accompanied by a deviation of the area from d^2-dependence.

Reference

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10120-3, Session 1

Vortex beams, vector beams, and Raman optical activity of glucose

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Due to the chiral (distinguishing right- from left-handed) nature of many important biomolecules, it is natural to posit methods of analyzing these molecules based on laser beams that share a similar asymmetry. Research up to this point has led to controversy as to whether beams carrying orbital angular momentum (OAM) are capable of interacting with chiral matter. Some studies indicate that OAM may not be capable of interaction with electric or magnetic dipole transitions, while others show that higher-order electric quadrupole field interactions are possible. We describe methods of Raman spectroscopy for resolving glucose using Laguerre-Gaussian (LG) laser modes with either circular polarization or spatially-inhomogeneous vector polarization (such as radial and azimuthal). Glucose is an important biomolecule with a chiral asymmetry and the ability to detect a Raman signal based on its structure would be an important finding in, for example, the measurement and monitoring of blood glucose levels in diabetics. Our attempts to detect and measure interactions with glucose mediated by OAM or circular polarization have resulted in inconsistent data that does not show conclusive evidence. Unlike linearly and circularly polarized light, vector vortex beams have a spatially varying polarization structure, the most common of which are radial and azimuthal polarization. In particular, when tightly focused, radial vortex beams take on a longitudinal component to their electric field with which one can detect vibrational modes inaccessible to linearly or circularly polarized beams. We will present our results on OAM and polarization in Raman spectroscopy with glucose.

10120-4, Session 1

Precise transverse alignment of a vectorial optical-field generator for complex optical field generation

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A vectorial optical field generator (VOF-gen) built in our laboratory is capable of generating arbitrarily complex beam cross section on a pixel-by-pixel basis, for which two liquid crystal spatial light modulators divided into four independently controlled sections are used as the spatially addressable retarders. The incident beam is relayed to each modulation section sequentially via several 4f systems. To obtain the desired complex optical field accurately, the incident beam should illuminate the same region on each section. However, there exists inevitable displacements among regions illuminated by the incident light on each section at times, which could lead to the output beam depart from the desired complex beam. In this work, we present an effective method to achieve precise transverse alignment of the four modulation sections. Based on the Fraunhofer diffraction theory and the properties of dove prism, the coordinate relationships among the four modulation sections are derived, which is important and helpful in designing patterns for complex beam. The displacement between the first section and subsequent ones are measured through applying crossing patterns with variable shifting. The metric is that the crossing patterns would overlap completely with no displacement between the two regions illuminated by the incident light. The measured displacement is then compensated via coordinate shifting to achieve accurate modulations for complex optical field generation. Various complex optical fields are generated and the experimental results show that the method is practicable and beneficial for the performance improvement of the VOF-gen.

10120-5, Session 2

Optical vortex generation by use of vector beam recorded azo-dye-doped liquid-crystal polymer composites

Moritsugu Sakamoto, Tomoyuki Sasaki, Tran M. Tien, Kohei Noda, Nagaoka Univ. of Technology (Japan); Nobuhiro Kawatsuki, Univ. of Hyogo (Japan); Hiroshi Ono, Nagaoka Univ. of Technology (Japan)

The optical vortex (OV), which has a helical wavefront and phase singularity at its optical axis, has been attracted attention in recent decades because of its unique optical characteristics, such as carrying orbital angular momentum and dark hole formation. For the experimental study of OV, an external spatial phase modulator is required to convert the wavefront of light wave emitted from the laser cavity between planes into a helical shape, and hence a number of OV generation methods have been proposed so far. In recent study, we also found that space variant three-dimensional anisotropic structures show OV generation properties. These anisotropic structures are passively formed in azo dye doped liquid crystals under vector beam illumination, which has cylindrical symmetry in their polarization distributions. In our previous report, OV generation with a topological charge of $l=\pm2$ was demonstrated, and hence we considered the use of this anisotropic structure to produce new types of OV generation system.

In this presentation, we report the experimentally investigated wavefront conversion properties of our OV generation system. Photo-induced anisotropic structures can be controlled by simply varying vector-polarized illuminating fields and their intensity distribution, and the OV generation with $l=\pm2$, ±4, ±6, ±8, and ±10 was demonstrated. The induced anisotropic structure can be re-initialized by turning it off and changing the illuminating polarization pattern, and hence our system has optical switching properties and controllability will enable the generation of a variety of OVs. Numerical simulations and experimental results showed that the OV generator has achromatic wavefront modulation properties for broadband spectra.

10120-6, Session 2

Generation of high-quality Laguerre-Gaussian beams for optical manipulation using phase-only spatial light modulator

Tomoko Otsu-Hyodo, Taro Ando, Yu Takiguchi, Yoshiyuki Ohtake, Haruyoshi Toyoda, Hamamatsu Photonics K.K. (Japan)

Laguerre-Gaussian (LG) beams are special kinds of light that carry orbital angular momenta and exhibit ring-shaped beam patterns. The LG beams can revolve small objects on the ring patterns when applied to optical tweezers. In fact, it is difficult to achieve the stable revolution of micrometer-sized polystyrene spheres in midwater without the help of light-independent supports such as gravity or glass surfaces. We study optical manipulation with LG beams generated by a phase-only spatial light modulator (SLM), which can precisely and flexibly modulate phase distribution of light. Recently, high-quality LG beams became available via various holographic complex-amplitude modulation methods, which can modulate both light phase and amplitude distributions simultaneously with the phase-only SLM. By focusing the high-quality LG beams by a high numerical aperture objective lens with careful optical adjustment, we achieved stable revolution of a micrometer-sized polystyrene sphere in midwater. Trapping properties of LG beams were evaluated by measuring the revolution motion of the trapped sphere using a high speed CMOS camera. Revolution radius was independent of the incident LG-beam power, suggesting that LG-beam trapping is achieved by the balance between the scattering and gradient forces of the LG beam. Furthermore, we observed excellent linearity between the revolution rate and the incident LG-beam power, indicating precise controllability of revolution motion by the LG-beam power. Comparison among different complex-amplitude modulation methods will also be shown. The present result contributes to enhance quantitativity of optical torque wrench as well as to measure absolute torque transferred from LG beam to small objects.

10120-7, Session 2

Optimizing beams with transverse vortices

Daryl Preece, Univ. of California, San Diego (United States); Halina Rubinsztein-Dunlop, The Univ. of Queensland (Australia)

It is widely known that beams that have optical vortices along the direction of propagation can be easily created in the laboratory. However, it is less well known that it is possible to create beams that have vortices transversely through the beam waist. Despite much work on beams with parabolic trajectories the creation of beams with transverse vortices are not well understood. Recently such beams have been created in the laboratory by means of computer-generated holograms. Though such beams can be created relatively easily optimization of the vortex structure requires the correct kinoform to be generated for the optical system.

Imprecise application of such kinoforms can generate multiple vortices at the beam focus, which may not be optimal in many applications. We discuss the properties of such beams and investigate the optimal geometry for creating beams with transverse vortices. Another important question surrounding such beams is the angular momentum that such beams could apply. Unlike beams with like LG beams Transverse vortex do not have an easily indexed winding number. We discuss the angular momentum associated with such beams.

Applications may exist in optical micro-manipulation, quantum communications and microscopy.

10120-8, Session 2

Creating light with orbital angular momentum using modified photon sieves

Olha V. Asmolova, Geoff P. Andersen, Monte D. Anderson, HUA, Inc. (United States); Michael A. Cumming, U.S. Air Force Academy (United States)

A new method for creating, measuring and sorting the orbital angular momentum (OAM) states of light using photon sieves is presented. Photon sieves are diffractive optical elements that consist of a series of microscopic holes distributed over the bright zones of an underlying Fresnel zone plate architecture. We have applied apodization techniques by changing hole locations, diameters, density, etc. to create all photon sieves with all manner of focusing properties. The simplest one introduces helical phase fronts in the diffracted beam, where each photon carries either an integer or non-integer OAM. Complex ones represent a combination of up to four various types of the photon sieves in one optical element and create mixed quantum states with the OAM changing as the beam propagates along the axis. The use of the modified photon sieves offers new applications for space imaging or quantum computing.

10120-9, Session 3

Controlled scattering as a novel tool for structured-light manipulation *(Invited Paper)*

Robert Fickler, Manit Ginoya, Manit Ginoya, Univ. of Ottawa (Canada); Robert W. Boyd, Univ. of Ottawa (Canada) and Univ. of Rochester (United States)

Light with a complex amplitude structure has been successfully investigated in fundamental and applied optical sciences. Mature devices such phase modulating spatial light modulators (SLM) have allowed a myriad of experimental findings in classical as well as quantum optics. However, state transformations that are more complex than simple phase manipulation are still hard or even impossible to realize.

We show that controlled scattering of structured light can be seen as a novel tool to achieve transformations, which haven't been possible before. By adapting recently developed techniques to control a complex, random scattering process and using a feedback signal, we demonstrate for example how an appropriate phase front shaping can lead to a programmable, custom-tailored mode sorting. We are able to sort up to 7 different orbital angular momentum (OAM) modes with accuracies of up to 98% to arbitrarily chosen spots and verify the coherence between the sorted positions, an essential feature for future applications in quantum experiments. Additionally, we successfully demonstrate the sorting of more complex light modes, such as superpositions of OAM modes and different p-modes, modes with different radial structure, a task which was not demonstrated before. We also investigate the possibility to send structured light modes through otherwise opaque material and test multi-mode fibers as scattering devices to increase transformation efficiencies. Our findings can be seen as first step to use a controlled coherent scattering process as a novel tool for complex transformations of structured light.

10120-10, Session 3

Mobius strips and twisted ribbons in the polarization of non-collinear singular optical beams

Enrique J. Galvez, Ishir Dutta, Kory Beach, Jon Zeosky, Colgate Univ. (United States); Behzad Khajavi, Colgate Univ. (United States) and Florida Atlantic Univ. (United States); Joshua A. Jones, Colgate Univ. (United States)

Light beams in non-separable superpositions of spatial mode and polarization produce space-variant patterns of polarization. When the beams meet in non-collinear geometries they create a 3-dimensional space-variant pattern that produces a new type of singular-optical situation. This entails 3-d twists in the orientation of the polarization ellipse along a closed curve. When one of the beams carries an optical vortex, the twists along a curve that includes the vortex form Mobius strips or twisted ribbons. We present our results to extract such patterns via projective measurements.

10120-12, Session 3

Creating variable spin states in diffraction-limited systems

Saharnaz Baghdadchi, Daryl Preece, Sadik Esener, Univ. of California, San Diego (United States)

The spin angular momentum of light has been used to rotate birefringent particles in the focal plane of optical tweezers systems. In order to achieve such rotation circularly or elliptically polarized light is applied to a high NA objective lens. Despite light with uniform polarization in the back focal plane of a high numerical objective lens the light at the focus is actually composed of an ensemble of polarization states that add up to give the resultant polarization in the focal plane. Correcting for this can give an optimized focal spot. Alternatively by creating spatially varying polarizations in the back focal plane arbitrary polarization states can be created in the focal plane. We discuss the creation of beam foci with spatially varying polarization states. Such foci can be used for novel manipulation of birefringent objects. By using a spatial light modulator with the capacity to change polarization and phase we can generate designed intensity and polarization patterns at the beam focus. Such technology may have applications in optical nano-manipulation, optical microscopy and nano-fabrication.

10120-13, Session 3

Geometrical interpretation of quantum weak measurement

C. T. Samlan, Nirmal K. Viswanathan, Univ. of Hyderabad (India)

A new kind of quantum measurement protocol introduced by Aharonov et al., in 1988, known as 'weak measurement' (WM) has lead to several unusual outcome. Post-selection of a weakly interacting pure quantum state results in amplified 'weak value' that lies outside its Eigenvalue spectrum. After many significant theoretical and experimental contributions the WM protocol has developed into an efficient measurement scheme to study weak effects in physical systems.

We revisit the quantum weak measurement (QWM) by sketching the dynamics of polarisation states on the Poincaré sphere and associated geometric phase. Our experimental arrangement comprises a laser beam as a source of pure state with two polarizers corresponding to pre- and post-selection of states, and a tilted wave plate placed between them to introduce weak interaction. The pre-selected state, a linearly polarised beam, represented as a point on the equator of the Poincaré sphere, interacts weakly with the wave plate resulting in a small spread of states along the S3 axis. Now, a projection orthogonal to the pre-selected state leads to two different geodesics on the Poincaré sphere through the poles, starting from both sides of the spread to the orthogonal point. The post-selection is made by moving the projection point slightly away from the orthogonal position on the equator so that both geodesics shift to the equator resulting in a rapid accumulation of geometric phase in the beam cross-section. As a consequence a gradient in linear momentum of topological origin develops which gives an amplified shift in the beam position.

10120-15, Session 4

Rabi-orbit coupling of polariton quantum vortices and swirling photonic pulses *(Invited Paper)*

Lorenzo Dominici, CNR-Istituto di Fotonica e Nanotecnologie (Italy); David Colas, Univ. Autónoma de Madrid (Spain); Antonio Gianfrate, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Carlos Sanchez Munoz, Univ. Autónoma de Madrid (Spain); Dario Ballarini, Milena De Giorgi, Giuseppe Gigli, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Fabrice P. Laussy, Univ. Autónoma de Madrid (Spain); Daniele Sanvitto, National Nanotechnology Lab. (Italy)

In this work we experimentally and theoretically investigate the 2D+t dynamics of moving and time oscillating quantum vortices.

These topological states are realized on resonant microcavity polaritons, a "quantum fluid platform" constituted by bosonic hybrid quasiparticles of

strongly coupled excitons and photons fields.

We exploit polaritons rooting a quantized vortex into Rabi oscillations, and using double-pulse coherent control to induce ad-hoc desynchronization able to shape a twisting vortex both in the two-dimensional fluid and hence in the emitted photonic pulse.

The effect can also be looked at in terms of the splitting of the original vortex between the two condensates of excitons and photons, or between the two normal modes of lower and upper polaritons, bearing independent frequencies, group velocities and decay rates. A continuous exchange of energy and angular momentum happens between the coupled condensates.

We propose to refer to such new composite states as "rartex". Topological bottle surfaces in the phase space can be associated to the rartex.

The new type of composite topologies result in the emission of photonic pulses which are structured light in both space and time. These photonic packets are characterized by one or more inner vortex tubes which spirals around the axis of propagation.

10120-16, Session 4

Parallel transport of fiber mode structure: orbit-orbit interaction

Nirmal K. Viswanathan, Pradeep T. Chakravarthy, Univ. of Hyderabad (India); Dinesh N Naik, Univ of Hyderabad (India)

That a paraxial light beam with spin angular momentum (SAM, ?) propagating in a helical trajectory leads to the appearance of Rytov-Vladimirsky-Berry (RVB) phase has been a topic of extensive research for the past several decades. Recently, using geometrical optics approximation, it was shown that variations in the beam propagation direction leads to generic parallel transport law – a beam with intrinsic orbital angular momentum (IOAM, l) behaves topologically similar to polarized beam containing only SAM but of magnitude proportional to the total angular momentum TAM = ??± l. We consider here the interaction of a beam with IOAM, propagating in a non-planar trajectory and hence with extrinsic orbital angular momentum (EOAM), in an inhomogeneous medium. The resulting rotation of transverse beam structure due to parallel transport of the LP fiber mode propagating along non-planar ray direction is attributed to the 'orbital' Berry phase. The experiment is carried out in a horizontally-held torsion-free two-mode optical fiber (TMF). Gaussian beam from He-Ne laser is raster scanned across the input end of the fiber using a rotating glass plate, mounted on a goniometer and kept in the Fourier plane between two matched lenses. The beam characteristics at the fiber output are captured using CCD camera. The mode transformation is simulated based on interference of the vector-vortex modes excited in the TMF. The LP mode rotation angle, calculated accurately using autocorrelation technique as a function of beam position at the fiber input shows topological features, mapped onto orbital Poincaré sphere.

10120-17, Session 4

Vortex-MEMS filters for wavelength-selective orbital-angular-momentum beam generation

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The waves with helical phase front was first identified and mathematically described in 1974 by Nye and Berry where screw wavefront dislocations in scattered wave trains were analysed. Later in 1992 Allen recognized that any helically phased light beam with an azimuthal term exp(il?), commonly known as optical vortex, inherently possesses an orbital angular momentum (OAM) and can be generated in lab. Utilization of OAM as an additional orthogonal basis of information carriers in both free space and optical fiber communication systems potentially enhances the transmission capacity tremendously. The current realizations of OAM-based transmission systems employ discrete, bulk optical devices, such as liquid crystal based spatial light modulators or separate phase plates. Such approaches require operations with free space beams as well as precise alignment of the elements. Hence, development of the compact, on-chip integrated optical components for generation, processing and detection of vortices is the next significant step towards robust, energy- and cost-effective OAM-based communication systems. In this work we experimentally report on generating wavelength-tunable OAM-carrying beams by integrating micro-sized stepped spiral phase plates (SPPs) on microelectromechanical system (MEMS) tunable Fabry-Perot optical filter. MEMS filters utilize surface micromachining technology and are suitable for mass fabrication in two-dimensional arrays. This vortex-MEMS filter, being capable of functioning simultaneously in wavelength and OAM domains at around 1550-nm, is considered as a compact, and cost-effective solution for simultaneous OAM- and WDM communications. Experimental spectra for azimuthal orders 1, 2 and 3 show OAM state purity > 92% across 30-nm wavelength range. A demonstration of multi-channel transmission is carried out as a proof of concept.

10120-18, Session 5

Multi-scale femtosecond laser structuring with structured light *(Invited Paper)*

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Singular optics is a very active modern field of research that manipulates structured light, namely electromagnetic fields endowed with phase or polarization singularities (also called optical vortices). Moreover, femtosecond laser structuring has already largely shown to be a very powerful approach for material advanced processing and manufacturing, which has been mostly performed with standard Gaussian beams. Thus, the combination of these two fields, corresponding to laser structuring with structured light, provides new experimental degrees of freedom that open promising perspectives in terms of material structuring, giving access to original structures that cannot be obtained with standard Gaussian beams.

While optical vortex beams were initially used for the structuring of surface topology, we demonstrated for the first time their high potential for bulk structuring [1], leading to multi-scale 3D architectures with sub-wavelength features with linear and nonlinear optical properties in innovative silver-containing glasses [2], as index change, silver cluster fluorescence, electric field induced second harmonic generation due to an unique ability of single-beam direct laser poling [3] and plasmonic properties [4]. We recently investigated the coupling influence of the spin momentum (beam polarization) with the orbital angular momentum (topological charge), leading to distinct material modification features, which may potentially further lead to all-optical super-resolution approaches for oxyde material structuring, so as to compete nanoscale manufacturing technologies.

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10120-19, Session 5

Arbitrary shaping of femtosecond non-diffracting beams for filamentation and ultrafast laser materials processing *(Invited Paper)*

François Courvoisier, Ismail Ouadghir-Idrissi, Remi Meyer, Remo Giust, Luc Froehly, Maxime Jacquot, John M. Dudley, FEMTO-ST (France)

Shaping complex light fields such as nondiffracting beams, provide important novel routes to control laser materials processing. Nondiffracting beams are produced from an interference between waves with an angle kept constant along the propagation direction. These beams are of outmost importance for laser materials processing because they offer invariant light-matter interaction conditions. We have used and developed several families of beams generated with phase and amplitude shaping and we will review their impact for laser surface processing and high aspect ratio laser processing in the bulk of transparent materials. Bessel beams and higher order Bessel beams allow for high aspect ratio channel drilling, elongated void creation in the bulk of transparent media, or tubular damage creation. We will also discuss the impact of accelerating beam shaping, ie beams with a curved main intensity lobe, to dice materials with a curved edge.

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10120-20, Session 5

Development and characterization of a microsnap-fit for optical assembly

Jannis Köhler, Yunus Kutlu, Sarah I. Ksouri, Cemal Esen, Andreas Ostendorf, Ruhr-Univ. Bochum (Germany)

Snap-fits are classified as interlocking connections and commonly used to assemble two or more components in a fast and cost efficient way. The mechanism is simply based on mechanical flexibility. Therefore, the applications cover a broad field ranging from automotive engineering to mobile phone design. By scaling and transferring the snap-fit mechanism into micrometer scale, advantages can also be utilized to assemble complex microsystems. In this paper, a microsnap-fit based on a cantilever design is developed and investigated by means of optical techniques only. Two-photon polymerization as micro-stereolithography is utilized to manufacture the microcomponents and the mechanical flexibility is analyzed by optical forces in a holographic optical tweezer setup. The locking mechanism is theoretically and experimentally characterized, e.g, the flexibility of the polymer with regard to the design is studied. It can be demonstrated that assembling as well as disassembling of microcomponents is achievable. These findings provide fast and easy assembling of complex microsystems in the fields of microrobotics, -sensors, and -mechanics.

10120-21, Session 5

Nanostructured elastomers for very small robots and photonic components *(Invited Paper)*

Diederik S. Wiersma, Lab. Europeo di Spettroscopie Non-Lineari (Italy)

We will review recent work on nano and micro structured polymers, in particular liquid crystalline elastomers, such as to realise small, complex, structures that deform when exposed to light. The goal is to create artificial arms, and legs, walking and swimming artificial micro creatures, and photonic components, like micro resonators that adapt to their environment.

10120-22, Session 6

Chiroptical interactions and transitions: parity, scale, and measurement

David L. Andrews, Univ. of East Anglia (United Kingdom)

The development of light beams with a vortex character in wave-front or polarization structure has brought a new focus upon the fundamental science of chiral interactions. A strong case can be made that, in order to understand the interplay and coupling of optical and material chirality on the nanoscale, it is crucial to account for the quantum aspects of light-matter interaction. In this paper, a quantum electrodynamical description is developed to formulate and address some of the key issues associated with spatial and temporal parity and scale, properly accounting for issues of measurability and measurement. Focusing attention upon the general symmetry features of a closed system state evolving under a complete system Hamiltonian, it is shown how parity rules determine the interplay of optical and material chirality, with specific regard to the chiral, enantiomerically selective, interactions.

10120-23, Session 6

Searching for the helical-gradient force on chiral molecules

Joshua A. Jones, Enrique J. Galvez, Brian Regan, Joshua Mills, Jackson Painter, Colgate Univ. (United States); Behzad Khajavi, Colgate Univ. (United States) and Florida Atlantic Univ. (United States)

We investigate a force that has been predicted to discriminate molecules by their chirality when they are in the presence of an optical field with a polarization helicity gradient. We investigate distinct experimental geometries for observing evidence of this force via the enantiometer separation of chiral molecules in racemic mixtures. We do this with singular-optical beams carrying a polarization helicity gradient across its transverse mode. Molecular diffusion and the dipole force – an intensity-gradient force – present challenges in the measurements of this force.

10120-24, Session 6

Chiral rotational spectroscopy

Jörg B. Götte, Nanjing Univ. (China) and Max-Planck-Institut für Physik komplexer Systeme (Germany) and Univ. of Glasgow (United Kingdom); Robert P. Cameron, Stephen M. Barnett, Univ. of Glasgow (United Kingdom)

Chirality pervades the natural world and is of particular importance to life, as the molecules that comprise living things are chiral and their chirality is crucial to their biological function. Our ability to probe and harness molecular chirality remains incomplete in many respects, however, and new techniques for chiral molecules are, therefore, highly sought after.

The basic property of a chiral molecule that is probed in typical optical rotation experiments using fluid samples is the isotropic sum of the electric-dipole / magnetic-dipole polarisability. The ability to determine orientated rather than isotropically averaged chiroptical information, in particular the individual optical activity polarisability components is highly attractive, as these offer a wealth of information about molecular chirality which is only partially embodied by the isotropic sum. At present such information can only be obtained, however, using an orientated sample as in a crystalline phase. The preparation of such samples is often unfeasible and even when it can be achieved, signatures of chirality are usually swamped by other effects.

Chiral rotational spectroscopy is a new technique that enables the individual determination of optical activity polarisability components, in a manner

that reveals the enantiomeric constitution of a sample whilst yielding an incisive signal even for a racemate. Chiral rotational spectroscopy could find particular use in the analysis of molecules that are chiral by virtue of their isotopic constitution and molecules with multiple chiral centres.

10120-25, Session 6

Spin polarization of alkali atoms by photoexciting alkali-rare gas collision pairs with circularly polarized light

Andrey E. Mironov, James G. Eden, Univ. of Illinois at Urbana-Champaign (United States)

The spin polarization of alkali atoms has been demonstrated to be of considerable significance to fundamental science, but also to biomedical imaging through the exchange of spin between an alkali atom and 4He and 129Xe. We report here a novel scheme for spin-polarizing alkali atoms through the photoassociation of thermal alkali-rare gas collision pairs. Driving such free-free molecular transitions with a circularly polarized (?+) optical field produces circularly-polarized (?-) ASE from the n2P3/2 state (n=5,6 for Rb, Cs). More than 70% of the Cs D2 line ASE (852.1 nm), for example, is circularly polarized. Furthermore, the degree of alkali n2P3/2 spin polarization can now be varied continuously by tuning the pump laser wavelength. All experiments were performed with no external magnetic field applied.

10120-26, Session 7

Exploiting the spatial profiles of light *(Invited Paper)*

Angela Dudley, CSIR National Laser Ctr. (South Africa); Andrew Forbes, Univ. of the Witwatersrand (South Africa)

An overview of the research done within the CSIR's National Laser Centre and the University of the Witwatersrand's Structured Light group will be presented. Here we implement digital holograms for the creation and detection of the spatial modes of light. We make use of modal decomposition theory to determine the numerous properties of light, from the modal content of laser beams to decoding the information stored in optical fields carrying orbital angular momentum. We demonstrate the versatility of these techniques to characterize both structured and vector fields with static and propagating optical fields. Finally, we show a holographic technique to realise a communication link using a densely packed spatial mode set where we experimentally multiplex and de-multiplex over 100 spatial modes.

10120-27, Session 7

High-order Poincaré sphere with flower modes possessing orbital angular momentum *(Invited Paper)*

Ting-Hua Lu, Teng-De Huang, National Taiwan Normal Univ. (Taiwan); Robert R. Alfano, The City College of New York (United States)

A hemi-cylindrical cavity composed of a cylindrical mirror and a gain medium is used to generate vector or scalar Laguerre-Gaussian modes and flower modes possessing orbital angular momentum. It depends on the symmetry of gain medium and cavities. On the other hand, we put another experimental setup after the above mentioned cavity which composed of a pair of non-polarization beam splitters, reflective mirrors, a pair of quarter-wave plates and a Dove prism. The incident laser passes through the Dove prism will change the topological charge l to –l.

Setting the angle of the two quarter-wave plates to +45 and -45 degrees leads to a right circular polarized and left circular polarized laser in each arm. We experimentally generate a superposition of right and left circular polarized structured mode at the end of setup which has inhomogeneous polarization distribution. Moreover, the polarization state can be mapped to the specific point on the high-order Poincaré sphere. The structured beams possessing orbital angular momentum and spatial variant polarization states may provide some applications.

10120-28, Session 7

Unusual electromagnetic disturbances

Robert Cameron, Univ. of Glasgow (United Kingdom)

Freely propagating light in the most general sense is governed by Maxwell's equations as written in the strict absence of charge. These demand in particular that the electric and magnetic fields are divergenceless. The electromagnetic field lines must therefore extend indefinitely or else form closed loops. Solutions of the former kind, such as a single plane electromagnetic wave, are well-known. Various solutions of the second kind, such as an electromagnetic knot, are known as well, but the idea as a whole remains relatively unexplored. We will discuss these unusual electromagnetic disturbances, their creation, their dynamics and their potential applications.

Our approach is centred upon the fact that any electromagnetic field must be expressible as a superposition of plane waves. If the field is monochromatic, the tips of the wavevectors of these waves must lie on the surface of a sphere in reciprocal space. Stable closed field line configurations can then be built by distributing these wavevectors in a suitably symmetrical manner whilst choosing their polarisations appropriately. Finally, solutions of this kind but with different frequencies can be added together to yield the most general form of freely 'propagating' electromagnetic disturbance. To produce such fields in practice at long wavelengths might require little more than suitable arrangements of antennas. At shorter wavelengths one may more usefully regard the solutions as being superpositions of various vector modes.

10120-29, Session 7

Array-specific propagation of flexibly structured ultra short pulses

Alexander Treffer, Martin Bock, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Ulrike Wallrabe, Univ. of Freiburg (Germany); Ruediger Grunwald, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Recently we demonstrated the flexible shaping of single and multiple structured beams, in particular Bessel-like beams and vortex beams, by liquid crystal spatial light modulators and MEMS-inspired axicon mirrors. Because of their low dispersion combined with structural flexibility, purely reflective piezo- or thermally actuated and reflective spiral phase plates of tunable tilt or phase stroke are well-suited for adaptively tailoring ultrafast wavepackets. With such beam shapers, high-fidelity pulse transfer was obtained even in the sub-3-cycle range. Here we report on experimental and theoretical studies of array-specific propagation phenomena in spatial and temporal domain which result from the interference of multiple coherent broadband pulses at Ti:sapphire laser wavelengths. It is shown that arrays of collectively or individually tunable shapers extend the flexibility of beam shaping by enabling to generate complex beams. The adaptive modification of far field patterns by addressing the phase signature of individual channels is an attractive approach for structured excitation and processing. For an improved theoretical description of coherent array effects, generalizations of the classical Talbot effect are required by considering finite, variable initial distributions of spectral phase, intensity and angular spectrum. Numerical simulations and experiments show how space-time coupling

effects at ultrashort pulse durations cause a propagation dependent change of spectral and temporal properties. The pulse transfer characteristics is relevant for evaluating parasitic coupling in multichannel processing, coherent coupling and designing complex interference maps with few-cycle optical pulses.

10120-30, Session 7

Cross section and polarization singularities in the twisted-photon absorption by atoms

Andrei Afanasev, The George Washington Univ. (United States)

We calculate transition amplitudes and cross sections for excitation of hydrogen like atoms by the twisted photon states, or photon states with large angular momentum projection on the direction of propagation. It is shown that when the transition rates are normalized to the local photon flux,the resulting cross sections for are singular near the optical vortex center [1], in close relation to the 'quantum core' concept introduced by Berry and Dennis. We also show that the photon state develops polarization singularity in the beam center due to circular dichroism of the photon absorption by atoms via higher multipoles.

[1]. A. Afanasev, C.E. Carlson, and A. Mukherjee, High-multipole excitations of hydrogen-like atoms by twisted photons near a phase singularity, Journal of Optics 18, 074013 (2016)

10120-31, Session 8

High-capacity optical communications using multiplexing of multiple orbital-angular-momentum beams *(Keynote Presentation)*

Alan E. Willner, The Univ. of Southern California (United States)

Optical communications has historically experienced capacity growth by multiplexing many channels, and space-division-multiplexing (SDM) appears to be the next domain to exploit. SDM can encompass multiple spatially overlapping "orthogonal" modes to achieve mode-division-multiplexing (MDM). Key advantages of modal orthogonality are the ability to efficiently (de)multiplex independent data streams and co-propagate them, all with little inherent crosstalk. An MDM approach using orbital angular momentum (OAM) has emerged as a potential method to efficiently multiplex many spatially over-lapping data-carrying beams. This presentation will highlight transmission of multiple OAM beams as well as the various technical challenges in realizing such a system.

10120-32, Session 8

Exploring topological phases in quantum walks of twisted light

Filippo Cardano, Univ. degli Studi di Napoli Federico II (Italy)

Topological invariants are ubiquitous in physical systems where they give rise to fascinating phenomena like quantized Hall conductance. Big efforts are put nowadays to engineer novel systems where, as a consequence of topological order, specific physical quantities are quantized and robust to local disorder. In this context, Quantum Walks (QW) are emerging as a precious resource, since they can be designed so as to simulate all topological phases manifesting in one-dimensional (1D) and two-dimensional systems (2D) of non-interacting particles. Here we present the implementation of a 1D QW protocol based on the orbital angular momentum (OAM) of light, that manifests the topological phases characterizing time-periodic systems (Floquet topological insulators) showing chiral symmetry. A control parameter determines the value of the topological invariants that characterize the system. Considering the OAM of light beam undergoing this quantum evolution, we found that statistical moments associated with the OAM spectrum contains information on the system topology. While varying the control parameter, these moments in the large step-number limit exhibit a sharp variation at the phase changes, and have marked differences in different phases. We demonstrated that this results from the properties of the energy bands of the system, and of the geometry of the associated eigenstates. The extension of this approach to higher dimensions, to different topological classes, and to other typologies of quantum phases, may offer new general instruments for the investigation of topological phases and quantum transitions in such complex systems.

10120-33, Session 8

Measuring the non-separability of optical fields

Bienvenu I. Ndagano, Hend Sroor, Melanie McLaren, Carmelo Rosales-Guzman, Andrew Forbes, Univ. of the Witwatersrand (South Africa)

Trapping microscopic particles, increasing the bandwidth of optical communication, modelling quantum channels, etc. These are just a few of the many fields where non-separable states of light, called vector beams, have found applications. Unlike traditional classical fields where the polarization vector is independent of the field amplitude, in vector beams the polarization and field amplitude are not separable. A common method of testing this non-separability is by observing the variation of the beam intensity through a rotating polarizer. Though this offer a qualitative analysis of the non-separability, it does not provide information about how vector is the observed mode. Measuring the degree of polarization at every point on the beam profile is one way to partially answer this question. However, it does not unveil the full picture of the state of the beam as a whole. Here, we present a complete toolbox to measure quantitatively, the degree of `vectorness' of spatial modes. The technique relies on the analogy between the classical non-separability of the degrees of freedom, and the quantum entanglement of bipartite systems. Measures of entanglement are well established in the field of quantum mechanics. Hence we borrow one of those measures, namely the concurrence, to derive a quantitative measure of the beam quality for vector modes. We demonstrate that our technique is efficient in determining the degree of non-separability for not only pure vector modes, but also modes with arbitrary degree of non-separability.

10120-34, Session 8

Quantum-key distribution with vector modes

Bienvenu I. Ndagano, Isaac Nape, Stirling Scholes, Melanie McLaren, Carmelo Rosales-Guzman, Univ. of the Witwatersrand (South Africa); Thomas Konrad, Univ. of KwaZulu-Natal (South Africa); Andrew Forbes, Univ. of the Witwatersrand (South Africa)

The state of a photon cannot be determined from a single measurement, unless the photon is in an eigenstate of some observable. The above statement is a fundamental property of quantum systems and is at the heart of quantum cryptography (QC) protocols, where information is commonly encoded in the polarization degree of freedom (DoF). Though such protocols are provably secure, they are limited in terms of bandwidth by the polarization DoF which only offers, at most, one bit of information per photon. Exploiting the spatial DoF in QC has been shown to increase the information capacity of single photons, thanks to the higher dimensional space the spatial DoF spans. Here, we demonstrate an implementation of QC based on hybrid space-polarization photonic states. In addition to providing higher dimensionality, these states have classical analogues in the form of vector vortex modes, which makes it possible to simulate the protocol classically. These vector vortex modes can be generated by manipulating the geometric phase of light with custom design wave plates. As a first approach, we experimentally simulated our high dimensional QC protocol using vector modes, and show an increase in information capacity close to the Shannon limit. We then realized the quantum experiment using hybrid space-polarization photonic states, and show an increase in information capacity well beyond the current state-of-the-art for identical dimensionality.

10120-14, Session PWed

Transmittance through mouse brain tissue with Gaussian and Laguerre Gaussian vortex beams

Lingyan Shi, Columbia Univ. (United States); Lukas Lindwasser, The City Univ. of New York (United States); Wubao Wang, The City College of New York (United States); Adrian Q. Rodriguez-Contreras, The City Univ. of New York (United States); Robert Alfano, The City College of New York (United States)

One of the key problems of optical imaging in neuroscience is to image deep within the brain. In addition, imaging resolution is always blurred due to scattering which needs to be overcome by selecting the coherent ballistic component. One solution is to select a wavelength in near-infrared (NIR) in one of the four optical tissue windows. Another method is to use the optimal types of spatial light beams. Studies showed that the magnitude of the scattering intensity decreased as OAM increased, suggesting the increase of transmission intensity with OAM. Therefore, the objective of this study was to examine transmission effects of Laguerre-Guassian beam with different orbital angular momentum (OAM) at various tissue thickness. In both ballistic and diffusive regions, transmittances of LG and G beams show no significant difference. The transition point from ballistic to diffusive region for the mouse brain tissue is determined at about 480 ?m. The observed transmittance of the LG and G beams shows the independence on OAM modes, which may be attributed to brain tissue's special structures and interference effects.

10120-48, Session PWed

Properties of null knotted solutions of Maxwell's equations

Gregory Smith, Paul Strange, Univ. of Kent (United Kingdom)

This presentation will discuss null knotted solutions to Maxwell's equations, their creation through 'Bateman's construction' [1, 2], and their relation to the Hopf-fibration [3, 4, 5]. These solutions have well-known, conserved properties related to their winding numbers [2]: e.g. energy; momentum; angular momentum; helicity. The current research has focused on Lipkin's Zilches [6], a set of ten little known conserved quantities within electromagnetic theory that have been explored mathematically, but for which there is still considerable debate over their physical interpretation. The aim of the work is to contribute to the discussion of these knotted solutions of Maxwell's equations by examining the relation between the knots, the Zilches, and their symmetries through Noether's theorem. We show that the Zilches demonstrate either a linear or a quadratic relation to the p-q winding numbers of the torus knots and can be written in terms of the total energy of the electromagnetic field. As part of this work a systematic multipole expansion of the vector potential of the knotted solutions is being carried out in an attempt to relate these properties to the fundamental topological charge proposed by Rañada [7].

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10120-35, Session 9

Single-beam acoustic tweezers *(Invited Paper)*

Jean-Louis Thomas, Institut des NanoSciences de Paris (France); Régis Marchiano, Diego Baresch, Univ. Pierre et Marie Curie (France)

Today, remote handling of tiny objects is efficiently performed by optical tweezers. They are quite efficient to handle particles ranging in size from a few micrometers to hundreds of nanometers and apply forces in the range of tens of picoNewton. However, for larger forces or larger objects, heating or photo-toxicity are recognized issues.

At equal incident beam power acoustical forces overtake by five orders of magnitude optical ones since radiation pressure is inversely proportional to the speed of propagation of the field. Furthermore, the large spectrum of frequencies covered by coherent ultrasonic sources provide a wide variety of manipulation possibilities from macro- to microscopic scales. For instance, acoustical levitation is an efficient technique for container-less processing and transportation of macroscopic matter in air, while acoustophoresis has provided a powerful strategy for on-chip manipulation, sorting and mixing of many microscopic particles and living organisms.

However, the various drawbacks in the state of the art studies using standing wave systems, have prohibited accurate manipulation of a single particle in three dimensions. Indeed, the single-beam concept of optical tweezers is fascinating but challenging since one expects and in most situation, observes, that the radiation pressure tends to push a scatterer in the beam propagation direction. I will present the trapping of elastic particles by the large radiation force of a single acoustical beam in the three dimensions. This stable potential well for elastic particles is obtained with a forward propagating helicoidal beam.

10120-36, Session 9

A mathematical toolbox for dark-ray optics *(Invited Paper)*

Albert Ferrando, Univ. de València (Spain); Miguel-Angel Garcia-March, ICFO - Institut de Ciències Fotòniques (Spain)

In order to achieve full control of dark rays, it is necessary to define a suitable mathematical framework to describe the optical beams in which they are embedded. Here we will provide new mathematical tools that will represent the first steps towards a full mathematical representation of dark ray optics.

In the first part we will introduce new tools specially adapted for the description of multisingular Gaussian vortex beams. We will define a new functional basis, the scattering modes, which permit a straightforward and analytical construction of multisingular Gaussian beams once its singularity structure is known at a reference plane. The mathematical properties of scattering modes will be presented as well as their analogies and differences with respect Laguerre-Gaussian (LG) modes. To end this part, we will provide some examples to clarify this procedure and, based on them, we

will show how to obtain analytical conditions for the generation of vortex-antivortex loops.

In the second part we will show how to implement discrete rotational symmetry into Gaussian solutions of the paraxial wave equation. We will perform the explicit construction in terms of scattering modes of Gaussian solutions owning discrete rotational symmetry, the so-called Discrete-Gauss states. We will analyze their distinguishing singularity structure, which has the form of dark beams presenting a dark focus where all singularities merge. Finally, we will discuss how to use standard optical elements to achieve full control of the dark rays trajectories of Discrete-Gauss states in analogy to ordinary bright rays in geometrical optics.

10120-37, Session 9

Light fields behind microstructures: study of the Babinet-principle in the Fresnel regime

Toralf Scharf, Myun-Sik Kim, Krishnaparvathy Puthankovilakam, Hans-Peter HERZIG, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

The Babinet's principle is a general theorem of diffraction that holds for electromagnetic waves. It compares an original diffraction pattern of a body with the diffraction pattern of the complement body and use the fact that the sum of both radiation patterns must be the same as the radiation pattern of the unobstructed beam. Often intensity is taken as characteristics for the radiation pattern and the phase fields are not discussed. Babinet's principle can be used to detect equivalence in size and shape.

In our contribution we study amplitude and phase behind amplitude structures. We demonstrate at different examples how the Babinet's principle can be applied to understand diffraction patterns for small structures and close to it in the Fresnel diffraction regime. We show simulation and measurements for structures like edges, slits and fine gratings with typical dimensions down to 2 micron for width or period.

Our main interest is to see how the Babinet's principle works at positions where phase singularities appear. At positions in space where one finds a singularity in phase field the intensity needs to vanish and disturbances lead to complex amplitude and phase fields. It is therefore interesting to compare the fields of both the original and complement structure.

Our results show that a reconstruction of the lightfield in the Fresnel regime is not possible considering only intensity values. Always amplitude and phase need to be considered. Additionally, at phase singularities field reconstruction leads to incomplete recovery, which will be discussed in more detail.

10120-38, Session 9

Monstar disclinations in high-order singular beams

Behzad Khajavi, Colgate Univ. (United States) and Florida Atlantic Univ. (United States); Enrique J. Galvez, Colgate Univ. (United States)

We investigate disclinations in the orientation of space-variant polarization patterns produced by collinear non-factorizable superpositions of high-order spatial modes and polarization. Asymmetric disclination patterns were formed by superpositions of spatial modes with asymmetric optical vortices. They give rise to monstar patterns of high order that can have a negative or positive disclination index. This has led to an examination of what constitutes a monstar. We present theoretical as well as experimental results.

10120-39, Session 10

a compact optical fibre trap based on a graded-index microlens and a principal component analysis algorithm for trap characterization in noisy environments

Jonathan Nylk, Martin V. G. Kristensen, Michael Mazilu, Anisha K. Thayil, Claire A. Mitchell, Elaine C. Campbell, Simon J. Powis, Frank J. Gunn-Moore, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Widespread use of optical manipulation in combination with advanced imaging techniques will be accelerated by compact, optically simple approaches which are readily integrated into advanced microscopy platforms. For example, optical manipulation has been combined with confocal, multi-photon, and STED microscopes. However, these typically require addition of optical components into the existing beam paths of the microscope, increasing complexity and potentially compromising image quality.

Optical fiber trapping (OFT) offers an ultra-compact and simple solution but compromises on trap quality due to the low numerical aperture (NA) and short manipulation distance of optical fibers. Tapered fibers can be fabricated but this further reduces the manipulation distance and requires access to specialist fabrication facilities.

Here we present a compact, single-beam, high NA OFT probe design based on a graded-index (GRIN) micro-objective lens and single-mode fiber. The OFT probe uses only off-the-shelf components, enables optical trapping at a distance of 200?m from the probe tip, and is compatible with inverted imaging systems.

A challenge with specialist imaging systems is the incompatibility between the specialist imaging modality of the platform and the imaging modality required for trap characterization, resulting in noisy and poor trap characterisation data. To overcome this challenge, we developed an adaptive image filter based on principal component analysis (PCA). The filter separates orthogonal degrees of motion in trap characterisation movies and strong stochastic noise can be removed before tracking, resulting in accurate characterisation.

We demonstrate the use of this PCA image filter for in situ characterisation of the GRIN lens OFT probe.

10120-40, Session 10

Near-diffraction limited direct imaging of patterned light fields for trapping

Guillaume Gauthier, Issac Lenton, Mark Baker, Matthew J. Davis, Halina Rubinsztein-Dunlop, Tyler W. Neely, The Univ. of Queensland (Australia)

Configurable trapping potentials are of great interest in cold atom physics, as they enable production of dynamical highly flexible fields that exhibit unprecedented stability and diverse geometries. Direct imaging can be used to create large area trapping potentials but is often overlooked due to its inability to correct for wavefront aberrations of the optical system [1]. This need not be a major disadvantage for a well-corrected optical system and brings advantages including the simplicity and speed of direct imaging. This is in contrast to the Fourier plane method which requires complex calculations to generate proper holograms and suffers from phase defects and speckle. For applications in cold atom trapping, these effects are especially detrimental as the atoms are sensitive to perturbations at the ~1% level of the optical potential.

Our approach uses off-the-shelf lenses and microscope objectives and is able to achieve 630(10) nm full width half maximum (FWHM) patterning resolution using a 0.45 NA objective, within 5% of the diffraction limit of the system, while imaging through 1.25 mm of glass. The light field patterning

is done using a digital micromirror device (DMD) which allows for dynamic trapping potentials due to its ability to store 13,889 frames and its 22 kHz full frame refresh rate. We use this method to pattern planar potentials for the purpose of cold atom experiments and have found that for atoms, which tend to respond relatively slowly to perturbations, it is possible to combine half-toning and time averaging to produce grey scale patterns, additionally allowing for pattern correction [2].

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10120-41, Session 10

Non-reciprocal topological energy transfer in an optomechanical system

Luyao Jiang, Jack Harris, Haitan Xu, David Mason, Yale Univ. (United States)

Non-reciprocal dynamics is under extensive investigation due to its significance in both theory (e.g., study of adiabatic theorem and p-t symmetry) and experiment (e.g., optical isolator). Recently, it was predicted that the energy transfer process between normal modes of open systems with a specific type of degeneracy known as an exceptional point (EP) could be achieved by topological operations, and that the outcome of these operations would be non-reciprocal. Here we demonstrate this non-reciprocal transfer of energy between two vibrational modes of a cryogenic optomechanical device using a tunable laser. We show that this non-reciprocity is topologically protected. We further induce an effective EP with an additional laser tone and observe similar dynamics. These results open up new directions in system control, as well as other dynamical processes of multimode systems that are robust against small perturbations.

10120-42, Session 10

Raman force measurements with femtosecond pulses

Ryan M. Khan, Bongsu Kim, Junghoon Jahng, Eric O. Potma, Univ. of California, Irvine (United States)

Raman spectroscopy can provide useful chemical information of nanostructures and molecules. We combine Raman spectroscopy with atomic force microscopy, through dual color photo-induced force microscopy (PiFM). In this modality, images with Raman contrast can be generated with a spatial resolution well below 10 nm at ambient temperature and pressure. Here we utilize this technique to visualize molecules on surfaces with high spatial and temporal resolution. Compared to previous Raman sensitive PiFM measurements, we employ femtosecond pulses and show that this technique is highly sensitive to the stimulated Raman scattering interaction in the molecule.

10120-43, Session 11

Towards Casimir force measurements with optical tweezers *(Invited Paper)*

Paulo A. Maia Neto, Luis Pires, Diney Ether Jr., Univ. Federal do Rio de Janeiro (Brazil); Ricardo S. Decca, Indiana Univ.-Purdue Univ. Indianapolis (United States); Nathan B. Viana, Univ. Federal do Rio de Janeiro (Brazil); Stefan Umrath, Gert Ingold, Univ. Augsburg (Germany); Daniel Martinez, Yareni A. Ayala, Felipe Siqueira Rosa, Herch Moysés Nussenzveig, Univ. Federal do Rio de Janeiro (Brazil)

We propose to use optical tweezers to probe the Casimir interaction between micro-spheres inside a liquid medium for geometric aspect ratios far beyond the validity of the widely employed proximity force approximation. This setup has the potential for revealing unprecedented features associated to the non-trivial role of the spherical curvatures. For a proof of concept, we measure femtonewton double-layer forces between polystyrene microspheres at distances above 400 nm by employing very soft optical tweezers, with stiffness of the order of fractions of a fN/nm. As a future application, we propose to tune the Casimir interaction between a metallic and a polystyrene microsphere in saline solution from attraction to repulsion by varying the salt concentration. With those materials, the screened Casimir interaction may have a larger magnitude than the unscreened one.

10120-44, Session 11

Confining Brownian motion of single nanoparticles in an ABELtrap *(Invited Paper)*

Maria Dienerowitz, Universitätsklinikum Jena (Germany); Thomas Heitkamp, Universitätsklinikum Jena (Germany); Thomas Gottschall, Jens Limpert, Friedrich-Schiller-Universität Jena (Germany); Michael Börsch, Universitätsklinikum Jena (Germany) and Friedrich-Schiller-Univ. Jena (Germany)

Trapping nanoscopic objects to observe their dynamic behaviour for extended periods of time is an ongoing quest. Particularly, sub-100nm transparent objects are hard to catch and most techniques rely on immobilisation or transient diffusion through a confocal laser focus. We present an anti-Brownian electrokinetic trap (pioneered by A. E. Cohen and W. E. Moerner) to hold individual FoF1-ATP synthase proteins in solution. We are interested in the conformational dynamics of this membrane-bound rotary motor protein that we monitor using single-molecule FRET. The ABEL trap is an active feedback system cancelling the nanoparticle's Brownian motion by applying an electric field. We show how the induced electrokinetic forces confine the motion of nanoparticles and proteoliposomes to the centre of the trap. We are able to trap single fluorescent 20nm particles up to two minutes and proteoliposomes containing a single fluorophore beyond 2s. This increases the observation time compared to free diffusion by a factor of 10000. Our system is based on single photon counting avalanche photodiodes (APD) and electro-optical beam deflector scanning units to monitor the position of the fluorescently labelled nanoparticles within the trapping region. A programmable FPGA chip controls the active feedback, beam steering as well as data acquisition.

10120-45, Session 11

Optical cell sorting with multiple imaging modalities

Andrew Bañas, OptoRobotix ApS (Denmark); Caro Carrissemoux, Univ. Gent (Belgium); Mark Villangca, Palima Darwin, DTU Fotonik (Denmark); Jesper Glückstad, Technical Univ. of Denmark (Denmark)

Early detection of diseases can save lives. Hence, there is emphasis in sorting rare disease-indicating cells within small dilute quantities such as in the confines of lab-on-a-chip devices. However, before diseased cells can be studied in isolation, it is necessary to identify them against normal healthy cells. With the richness of visual information, a lot of microscopy techniques have been developed and have been crucial in biological studies. To utilize their complimentary advantages we adopt both fluorescence and brightfield imaging in our optical cell sorter. Brightfield imaging has the advantage of being non-invasive, thus maintaining cell viability. Fluorescence imaging, on the other hand, takes advantages of the chemical specificity of fluorescence markers and can validate machine vision results from brightfield images. Visually identified cells are sorted using optical manipulation techniques. Scattering forces from beams actuated via efficient phase-only modulation have been adopted. This has lowered the required laser power for sorting cells to a tenth of our previous approach, and also makes the cell sorter safer for use in clinical settings. With the versatility of dynamically programmable phase spatial light modulators, a plurality of light shaping techniques, including hybrid approaches, can be utilized in cell sorting.

10120-46, Session 11

Wavelength-tunable optical-fiber tweezer

Esmaeil Mobini, Arash Mafi, The Univ. of New Mexico (United States)

We present for the first time a wavelength tunable fiber-based optical tweezer using a graded index multimode optical fiber (GIMF). Optical fiber tweezer is a viable replacement for the bulky objective-based tweezers because of the low-cost and user-friendly operation and maneuverability. The proposed optical fiber tweezer consists of a GIMF spliced to a single mode fiber into which a wavelength tunable laser is launched. The exit field at the end-facet of the GIMF is used for tweezing. The GIMF setup is capable of generating a tunable-distance optical trap over a hundred microns by just tuning the laser wavelength. The position of the optical trap can also be customized with the proper design of the GIMF and straining the fiber. The length of the GIMF also plays an important role in the operation of the device. This length needs to be fined-tuned only over less than 500 microns due to the self-imaging properties of the beam propagating in a GIMF; therefore, the necessary length adjustments can be easily done by polishing the end-facet of the fiber. The numerical results also show that as the optical trap moves farther away from the GIMF tip, the optical trap gets weaker. The results also show that the minimum input power to meet the stability conditions for a particle with a radius of 0.1 micron is around 400 mW.

10120-47, Session 11

Light robotics: an all-optical micro- and nano-toolbox

Jesper Glückstad, Technical Univ. of Denmark (Denmark)

Optical nanoscopy can already today surpass the classical far-field diffraction limit and provide optical resolutions down to a few nanometers. Strongly linked to this is the rapidly emerging field of light-based 3D printing using powerful approaches offered by e.g. nonlinear photo-polymerization processes. It is now possible to 3D laser-print nanoscopic structures with a voxel resolution down to below a few tens of nanometers. By adding a third key scientific accomplishment; the ability of focused light to capture, trap and manipulate tiny objects - a triangulation of new functionalities required for all-optical light-driven robotics can be achieved. Integrating all these amazing light-based breakthroughs we can create the conditions for harnessing the functionalities required to fully develop the concept of so-called Light Robotics.

Conference 10121: Optical and Electronic Cooling of Solids II

Wednesday - Thursday 1 –2 February 2017

Part of Proceedings of SPIE Vol. 10121 Optical and Electronic Cooling of Solids II

10121-1, Session 1

Enhanced cooling of Yb:YLF using astigmatic Herriott cell *(Invited Paper)*

Aram Gragossian, Junwei Meng, Mohammadreza Ghasemkhani, Alexander R. Albrecht, The Univ. of New Mexico (United States); Mauro Tonelli, Univ. di Pisa (Italy); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Optical refrigeration of solids requires crystals with exceptional qualities. Crystals with external quantum efficiencies (EQE) larger than 99% and background absorptions of 4?10-4cm-1 have been cooled to cryogenic temperatures using non resonant cavities. Estimating the cooling efficiency requires accurate measurements of the above mentioned quantities. Here we discuss measurements of EQE and background absorption for two high quality Yb:YLF samples. For any given sample, to reach minimum achievable temperatures heat generated by fluorescence must be removed from the surrounding clamshell and more importantly, absorption of the laser light must be maximized. Since the absorption coefficient drops at lower temperatures the only option is to confine laser light in a cavity until almost 100% of the light is absorbed. This can be achieved by placing the crystal between a cylindrical and spherical mirror to form an astigmatic Herriott cell. In this geometry light enters through a hole in the middle of the spherical mirror and if the entrance angle is correct, it can make as many round trips as required to absorb all the light. At 120 K 60 passes and 150 passes at 100K ensures more than 95% absorption of the laser light. 5 and 10% Yb:YLF crystals placed in such a cell cool to sub 90K temperatures. Non-contact temperature measurements are more challenging for such a geometry. Reabsorption of fluorescence for each pass must be taken into account for accurate temperature measurements by differential luminescence thermometry (DLT). Alternatively, we used part of the spectrum that is not affected by reabsorption.

10121-2, Session 1

Investigation of novel fluorine-based single-crystalline materials for anti-Stokes cooling *(Invited Paper)*

Azzurra Volpi, Giovanni Cittadino, Univ. di Pisa (Italy); Alberto Di Lieto, Univ. di Pisa (Italy) and NEST (Italy); Mauro Tonelli, Univ. di Pisa (Italy) and NEST (Italy)

Optical cooling of solid materials relies on the process of anti-Stokes fluorescence for heat removal from the system. Laser excitation tuned above the mean emission wavelength of the electronic transition induces spontaneous emission of blue-shifted photons where the extra-energy is supplied by annihilation of lattice phonons, resulting in net bulk cooling if the decay is predominantly radiative. High-quality Yb doped fluoride single-crystals have definitely enabled cryogenic and sub-100K operations and theoretical calculations prospect further improvements towards the liquid nitrogen temperature, improving the material purity. Truly vibration-free and largely miniaturizable, such a technology is much sough-after for space related applications.

So far the best bulk cooling performances were achieved with Yb doped LiYF4 (YLF) active media, however other fluorides single crystals have been little studied. In this work we report on first observation of optical cooling of a novel multisite crystal, KYF4:Yb, that is different from YLF both in the crystallographic structure and because Yb can be host in 6 different sites. The KYF4 is largely interesting for its low phonon cut-off energy, which effectively suppresses non-radiative heat generating processes. A comparison with recent results obtained with Yb-doped YLF single crystals, and its isomorph LLF are presented. Crystal growth details, assessment of crystal quality and comparative spectroscopic analyses are presented, along with investigation of impurities mediated processes and their influence on anti-Stokes efficiencies.

10121-3, Session 1

Laser refrigeration of sodium-yttrium-fluoride nanowires *(Invited Paper)*

Xuezhe Zhou, Bennett E. Smith, Paden B. Roder, Peter J. Pauzauskie, Univ. of Washington (United States)

Hexagonal sodium-yttrium-fluoride (?-NaYF4) are currently being studied for a wide range of applications including color displays, solar cells, photocatalysis, bio-labeling, bio-imaging, and photodynamic therapy. ?-NaYF4 has also been predicted to be a promising host material for laser-refrigeration-of-solids (LRS). However, due to challenges with growing Czochralski ?-NaYF4 single-crystals, laser refrigeration of ?-NaYF4 has not been achieved. Here we use a low-cost, scalable hydrothermal synthesis method to prepare ?-NaYF4 nanocrystals. We demonstrate the first time laser ?refrigeration of Yb?-doped ?-NaYF4 nanocrystals in heavy water (D2O) with a single-?beam near?infrared (NIR) optical trapping. Forward-scattered laser radiation from optically-trapped NWs creates a dynamic interference pattern within the microscope's back-focal-plane that is detected with a high-speed silicon quadrant-photodiode (QPD). The time-dependent photovoltage signal from the QPD is then Fourier-transformed in order to compute the resulting power spectral density (PSD). The local refrigeration of the individual nanocrystal in D2O is quantified through the analysis of PSD. The individual ?-NaYF4 nanocrystals show maximum local cooling by 9°C below ambient conditions. Heat is extracted out of the lattice through anti?Stokes photoluminescence of Yb excited?states ?mediated optical phonon absorption. Single-particle experiments also show reversible cation-exchange reactions at the crystal / water interface. This can be applied to control the synthesis of nanocrystals with different shapes and compositions.

10121-4, Session 1

Optical refrigeration of Yb3+:LuLiF4 crystal

Biao Zhong, Hao Luo, Yanling Shi, Jianping Yin, East China Normal Univ. (China)

The high quality Yb-doped fluoride crystals have broaden prospects for optical refrigeration. We demonstrate that the Yb3+:LuLiF4 crystal can be cooled to the temperature below the current limit of thermoelectric cooler (~180 K). The optical refrigeration of 3.23wt.% Yb3+:LuLiF4 crystal with the geometry of 2 mm?2 mm?5 mm is demonstrated. The sample is supported by two fibers with the diameter of 200 ?m in a ~10-3 Pa vacuum chamber. The environment temperature is about 294.5 K. The 38.7 W CW laser at wavelength of 1019 nm is adopted to irradiate the sample. The cooling setup is a single pass configuration. After the crystal is pumped by the laser for 20 minutes, we measured the temperature of the sample utilizing the DLT methods and found the sample is cooled down to ~178 K by the laser. These experimental results further demonstrate the promising prospect of the Yb3+:LuLiF4 crystal for the cryogenic optical refrigeration.

10121-5, Session 1

Advances in laser cooling of Tm:YLF crystals

Saeid Rostami, Alexander R. Albrecht, The Univ. of New Mexico (United States); Mauro Tonelli, Univ. di Pisa (Italy); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

We investigate high power laser cooling in Tm:YLF crystals both in ambient pressure and high vacuum. For this purpose, we have constructed a high power CW OPO broadly tunable from 1755 nm to 2000 nm. By using this tunable source, laser cooling for (3 mm3) 1% doped Tm:YLF crystal was observed from 1801 nm to 2000 nm. Cooling efficiency of the sample, external quantum efficiency (EQE), background absorption and optimum laser cooling wavelength are extracted from laser induced temperature modulation spectrum (LITMoS) test on the cooling sample. To improve cooling performance, we have designed multiple pass non-resonant cavities to maximize the absorption of the laser light inside the sample. We setup multiple pass cavities in a high vacuum chamber to reduce convective heat load and enhance laser cooling results.

10121-6, Session 2

Electroluminescent refrigeration versus laser cooling: what the new high-efficiency solar cells tell us *(Keynote Presentation)*

Eli Yablonovitch, Tianyao P. Xiao, Univ. of California, Berkeley (United States)

No Abstract Available.

10121-7, Session 2

Efficient electroluminescent cooling with a light-emitting diode coupled to a photovoltaic cell

Tianyao P. Xiao, Univ. of California, Berkeley (United States); Kaifeng Chen, Parthiban Santhanam, Shanhui Fan, Stanford Univ. (United States); Eli Yablonovitch, Univ. of California, Berkeley (United States)

The new breakthrough in photovoltaics, exemplified by the slogan “A great solar cell has to be a great light-emitting diode (LED)”, has led to all the major new solar cell records, while also leading to extraordinary LED efficiency. As an LED becomes very efficient in converting its electrical input into light, the device cools as it operates because the photons carry away entropy as well as energy. If these photons are absorbed in a photovoltaic (PV) cell, the generated electricity can be used to provide part of the electrical input that drives the LED. Indeed, the LED/PV cell combination forms a new type of heat engine with light as the working fluid. The electroluminescent refrigerator requires only a small amount of external electricity to provide cooling, leading to a high coefficient of performance.

We present the theoretical performance of such a refrigerator, in which the cool side (LED) is radiatively coupled to the hot side (PV) across a vacuum gap. The coefficient of performance is maximized by using a highly luminescent material, such as GaAs, together with device structures that optimize extraction of the luminescence. We consider both a macroscopic vacuum gap and a sub-wavelength gap; the latter allows for evanescent coupling of photons between the devices, potentially providing a further enhancement to the efficiency of light extraction. Using device assumptions based on the current record-efficiency solar cells, we show that electroluminescent cooling can, in certain regimes of cooling power, achieve a higher coefficient of performance than thermoelectric cooling.

10121-8, Session 2

A design of a PhC-enhanced LED for electroluminescence cooling

Zheng Li, Xue Jin, Rajeev Jagga Ram, Massachusetts Institute of Technology (United States)

It is known that the wall-plug efficiency (WPE) of a light-emitting diode (LED) can exceed unity and that electroluminescence cooling (ELC) happens in this scenario. However, it is difficult to observe the associated temperature drop due to the relatively small cooling power and the overwhelming heat flux from the ambient. In this work, we design a photonic crystal (PhC) enhanced LED which has smaller surface area as well as thermal mass compared with an encapsulated LED. We also present thermal models to evaluate the temperature drop of the LED in air and vacuum.

10121-9, Session 2

Thermophotonic cooling and energy transport in intracavity semiconductor structures

Jonna Tiira, Ivan Radevici, Aalto Univ. (Finland); Teemu Hakkarainen, Tampere Univ. of Technology (Finland); Pyry Kivisaari, Arto J. Aho, Aalto Univ. (Finland); Antti Tukiainen, Mircea Guina, Tampere Univ. of Technology (Finland); Jani Oksanen, Aalto Univ. School of Science (Finland)

Despite the very high internal quantum efficiencies reported for GaAs based light emitters [1], electroluminescent or photoluminescent cooling of conventional semiconductor structures has not yet been feasible at technologically relevant power levels [2,3]. To overcome and understand the main obstacles in fully exploiting the high IQE for optical cooling, we study thermophotonic (TPX) heat transport in cavity coupled light emitters. Our structures consist of a double heterojunction (DHJ) LED with a GaAs active layer and a corresponding DHJ or a p-n-homojunction photodiode, both enclosed within a single semiconductor cavity to eliminate the light extraction challenges. [4]

Our setup enables a simple IV measurement based approach for quantifying the key loss mechanisms affecting the light emission efficiency, such as the mirror, light extraction, nonradiative, and detection losses [4]. Our results on the present intracavity devices and our most recent measurements for the carrier lifetimes of the next device design with optimized materials suggest that we are quickly approaching the tipping point between the heating and cooling regimes, estimated to correspond to the overall loss level of 10-20 %. The optimization of the materials as well as the control of the material interfaces additionally provides the possibility to tailor the device performance to further reduce the loss level. We will report our most recent advances aiming to demonstrate the cooling effect and related effects of materials, design and fabrication details on the device performance.

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10121-10, Session 2

Surface phonon polaritons as a source of laser cooling perturbation *(Invited Paper)*

Galina Nemova, Raman Kashyap, Ecole Polytechnique de Montréal (Canada)

The idea to cool with light was proposed by Pringsheim in 1929.1 He proposed the use of anti-Stokes fluorescence to cool sodium vapour. However, it took until 1995 to demonstrate this principle: a Yb3+ doped ZBLANP sample was cooled with a laser with the temperature drop only 0.3K starting from room temperature.2 Since then, cooling has been obtained with Yb3+, Tm3+, and Er3+ ions doped in a wide variety of low-phonon glasses and crystals. The latest record temperature of ~91K was achieved with Yb3+:YLF in 2015.3 One of a number of applications of laser induced cooling is in optical solid state cryo-coolers, which can achieve temperatures as low as ~80K. They are free from liquids and operate with reliable diode pump systems. Being all optical, they are free from mechanical vibrations and electro-magnetic interference. To design optical solid state cryo-coolers it is very important to investigate how laser cooling process changes under the influence of different samples placed near the laser cooled sample.

In this work we investigate laser cooling of a Yb3+:YAG sample placed near YAG and SiC samples, at room temperature. All three samples Yb3+:YAG, YAG, SiC can support surface phonon polaritons (SPhPs) in different frequency ranges. We have shown that if two samples are placed in close proximity, that is at a distance less than the dominant wavelength of thermal radiation ? = c?/kT, and if the SPhPs propagating in the sample being laser cooled and SPhPs propagating in the adjacent sample at room temperature are coupled, the laser cooling process can deteriorate significantly, otherwise the SPhPs do not substantially influence the cooling process even if the distance between the samples is less than ?. The influence of coupled SPhPs on the laser cooling process in the case of samples with different sizes is investigated.

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10121-26, Session PWed

Lock-in thermography approach for imaging the efficiency of light-emitters and optical coolers

Ivan Radevici, Jonna Tiira, Aalto Univ. (Finland); Jani Oksanen, Aalto Univ. School of Science (Finland)

Electroluminescent (EL) and photoluminescent (PL) cooling represent cooling techniques extracting heat from a solid by emission of photons receiving a part of their energy from lattice. While PL cooling has been demonstrated on a large range of rare-earths doped glasses, observing luminescent cooling of semiconductors providing larger cooling power density [1-3] is still a great challenge, further complicated by the difficulty to accurately measure the associated near unity quantum efficiencies (QE).

One of the most suitable methods to measure very high QEs is based on a calorimetric technique combining light-emission measurement to temperature measurements probing the heat deposited in a semiconductor by non-radiative recombination [4]. This approach relies on the fact that the absorbed power must be converted into either light or heat: a fractional increase of one is accompanied by a fractional decrease of the other. Conventionally photoacoustic techniques, thermistors or PL peak position shifts [5] are used to measure a single value for the temperature.

We combine the calorimetric principles with lock-in thermography (LIT) [6] and conventional luminescence microscopy to enable spatially resolved measurement of the QE. This enables spatially resolved characterization and localization of the losses of e.g. the record efficient thin film emitters [5] and double diode structures we use [7] to study photon and heat transport within semiconductor cavities. We report our results on using LIT to measure and compare the PL and EL efficiencies of thin-film light emitters without their substrates to learn more about difference in EL and PL cooling approaches.

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10121-27, Session PWed

Demonstration of payload cooling in optical refrigerator prototype

Aram Gragossian, Junwei Meng, Mohammadreza Ghasemkhani, Alexander R. Albrecht, The Univ. of New Mexico (United States); Bernardo Farfan, Guy Symonds, Thermodynamic Films (United States); Eric Lee, The Univ. of New Mexico (United States); Richard Epstein, Thermodynamic Films (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

The first ever all solid state optical cooler is discussed. Laser cooling of solids has advanced immensely and the available crystals can be used to cool temperature sensitive sensors. By connecting the crystal to a thermal mass via a thermal link, we have been able to cool a sensor by more than 30 degrees. Good thermal conductivity, fluorescence rejection, and efficient heat removal, are a few of the issues that need to be addressed before any cooling in the sensor is achieve. Shielding the thermal load from fluorescence was the most important problem that needed to be remedied.

10121-11, Session 3

Resolved sideband Raman cooling of optical phonons in semiconductor materials *(Invited Paper)*

Qihua Xiong, Nanyang Technological Univ. (Singapore)

The radiation pressure of light has been widely used to cool trapped atoms or the mechanical vibrational modes of optomechanical systems. Recently, by using electrostrictive forces of light, spontaneous Brillouin cooling and stimulated Brillouin excitation of whispering-gallery type acoustic modes have been demonstrated. The laser cooling of specific lattice vibrations in solids (i.e., phonons) proposed by Dykman in 1980s, however, still remains sparsely investigated. Here we demonstrate the first strong spontaneous Raman cooling and heating of longitudinal optical phonon (LOP) with a 6.23 THz frequency in polar semiconductor zinc telluride (ZnTe) nanobelts, in which strong exciton-LOP Frohlich interaction sustains. We use the exciton to resonate and assist photo-elastic Raman scattering from LOPs due to the large exciton-LOP coupling. The cooling (heating) is mediated by detuning the laser pump to lower (higher) energy resolved-sideband, and spontaneous scattering photon resonates with exciton at anti-Stokes (Stokes) side, which beat and photo-elastically attenuate (enhance) the dipole oscillation of the optical phonons.

10121-12, Session 3

Optimization of anisotropic photonic density of states for Raman laser cooling

Indronil Ghosh, Yin-Chung Chen, Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)

Raman laser cooling of solids requires the anti-Stokes up-conversion of incident light through the annihilation of THz-frequency Raman-active phonons from the system. The primary fundamental challenge to achieve Raman cooling is therefore to significantly increase the probability of anti-Stokes optical scattering relative to Stokes scattering. This can be accomplished by either using excitonic resonances intrinsic to the material, or by modifying the photonic density of states (DoS) of the device structure extrinsic to the material. While we recently showed analytically that net cooling can be achieved by using a 3-D photonic crystal having a complete photonic band gap, the complexity of fabricating such a 3-D structure renders the experimental demonstration very challenging. In this study, we combine the anisotropic feature of the optical DoS of photonic crystals and the Raman selection rules of the host material to demonstrate that a complete 3-D band gap is not necessary for suppressing the Stokes scattering process. Instead, we show how optimizing the relative alignment of the material crystal (Raman selection rules) with respect to the photonic structure (anisotropic DoS) of some simple 2-D and 3-D photonic crystal structures can lead to Stokes suppression. A strong contrast between Stokes and anti-Stokes scattering can be achieved when the directions of higher Stokes scattering intensity are aligned with one of the partial band gaps of the photonic structure. These results suggest a simpler approach to engineering the photonic DoS and can potentially facilitate the experimental demonstration of net Raman cooling in solids.

10121-13, Session 3

Defect-mediated photoluminescence up-conversion in cadmium sulfide nanobelts

Yurii Morozov, Masaru K. Kuno, Univ. of Notre Dame (United States)

The concept of optical cooling of solids has existed for nearly 90 years ever since Pringsheim proposed a way to cool solids through the annihilation of phonons via phonon-assisted photoluminescence (PL) up-conversion. In this process, energy is removed from the solid by the emission of photons with energies larger than those of incident photons. However, actually realizing optical cooling requires exacting parameters from the condensed phase medium such as near unity external quantum efficiencies as well as existence of a low background absorption. Until recently, laser cooling has only been successfully realized in rare earth doped solids.

In semiconductors, optical cooling has very recently been demonstrated in cadmium sulfide (CdS) nanobelts as well as in hybrid lead halide perovskites. For the former, large internal quantum efficiencies, sub-wavelength thicknesses, which decrease light trapping, and low background absorption, all make near unity external quantum yields possible. Net cooling by as much as 40 K has therefore been possible with CdS nanobelts.

In this study, we describe a detailed investigation of the nature of efficient anti-Stokes photoluminescence (ASPL) in CdS nanobelts. Temperature-dependent PL up-conversion and optical absorption studies on individual NBs together with frequency-dependent up-converted PL intensity spectroscopies suggest that ASPL in CdS nanobelts is defect-mediated through involvement of defect levels below the band gap.

10121-14, Session 3

Photoluminescence Investigation of CdS nanoribbons using a tunable VECSEL source

Daniel A. Bender, Seth D. Melgaard, Brian Swartzentruber, Sandia National Labs. (United States); Alexander R. Albrecht, The Univ. of New Mexico (United States); Jeffrey Cederberg, MIT Lincoln Lab. (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

We report on our attempt to laser cool CdS nanoribbons. Laser pumping is accomplished using a custom CW intra-cavity frequency-doubled VECSEL source and was designed to allow laser pumping across the bandgap of CdS. The laser source is tunable from approximately 510-520 nm and is optically pumped with an 808 nm diode laser. CdS nanobelt samples are mounted in an optical cryostat on a holey Si substrate and interrogated by pump-probe spectroscopy. Photoluminescence from a 473 nm diode probe laser is resolved with a spectral resolution of 0.07 nm. Additionally, we present time-dependent results on thermal modeling of suspended CdS nanobelts van der Waal bonded across a 5 um void on a Si substrate.

10121-15, Session 3

Investigation into the origin of parasitic absorption in InGaP/GaAs double heterostructures

Nathan Giannini, Alexander R. Albrecht, Zhou Yang, Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Parasitic absorption in InGaP/GaAs double heterostructures (DHS) has inhibited the realization of net cooling despite samples reaching an external quantum efficiency (EQE) of 99.6%. This parasitic absorption manifests itself by generating heat in the sample and, therefore, is measureable. Possible sources include bulk parasitic absorption in GaAs or InGap, as well as interface absorption, either at the air/InGaP interface, the InGaP/GaAs interface, or the InGaP-substrate interface. In general, whereas bulk parasitic absorption is caused by impurities and defects, interface (or surface) parasitic absorption is thought to be caused by dangling bonds. Prior studies of bulk parasitic absorption have shown that GaAs is unlikely to be the source of this parasitic heating, and so this study investigates the bulk and air/InGaP interface contributions to the sample background (parasitic) absorption. These samples were prepared by removing a layer of InGaP from a DHS, using a HCl-acetic acid-H¬2O2 etch solution, followed by jet-etching of the GaAs layer using NH4OH-H2O2. Additional samples were also prepared from InGaP layers grown on GaAs wafers with an AlAs release layer. The reason for this was to screen for discrepancies between grown DHSs and single layer pieces. These samples were subsequently bonded to a piece of low absorption (<10-5 cm-1, Suprasil) glass. The sample is then tested by using the experimental technique Z-scan.

10121-16, Session 3

Investigation of the laser cooling cycle in the time domain

Jan F. Schmidt, Timo Raab, Jannis Oelmann, Denis V. Seletskiy, Univ. Konstanz (Germany)

Upon excitation of a material below its fundamental transition, cooling of the lattice results if the subsequent emission is predominantly radiative. Despite overwhelming experimental success, it remains a challenge to understand the microscopic nature of detrimental processes that can even prevent cooling. We apply ultrafast spectroscopy to resolve the laser refrigeration cycle in the time domain. Strong evidence for lattice cooling on picosecond timescales in bulk GaAs/InGaP double-heterostructures and GaAs/AlGaAs quantum wells establishes the non-local nature of the parasitic mechanisms. Further precision measurements investigating long-time dynamics are currently underway to resolve detrimental heating in bulk GaAs for the first time.

10121-17, Session 4

Practical challenges for radiation-balanced lasers *(Invited Paper)*

Steven R. Bowman, U.S. Naval Research Lab. (United States)

Radiation Balanced Lasers (RBL) use cooling from spontaneous emission to offset waste heat generation. This technique offers the potential for very high power operation without thermo-optic distortions or damage. Nevertheless establishing and maintaining radiation balance poses interesting problems for the laser designer. An analysis of RBL's sensitivity to material losses, intensity variation, and temperature will be presented. This comparison of simulations and experiments is intended to assist in the design of future high power systems.

10121-18, Session 4

Internal cooling of fiber and disc lasers by radiation balancing and other optical and phonon processes: a new AFOSR MURI program *(Invited Paper)*

James G. Eden, Univ. of Illinois at Urbana-Champaign (United States); John M. Ballato, Clemson Univ. (United States); Michel J. F. Digonnet, Stanford Univ. (United States); Peter D. Dragic, Andrey E. Mironov, Univ. of Illinois at Urbana-Champaign (United States); Stephen C. Rand, Univ. of Michigan (United States)

A new AFOSR MURI program, devoted to the pursuit of cooling solid state lasers internally, is underway and will be described. Comprising research teams from four universities, this program will focus on fiber and disc lasers and the demonstration of optical and/or phonon-based processes capable of maintaining beam quality as power loading of the medium rises. Emphasis will be placed on leveraging novel resonator designs to enhance a targeted optical field-material interaction such that localized cooling occurs within the gain medium. Examples will be given of two systems that are being pursued initially.

10121-19, Session 4

Multidisciplinary approaches to radiation-balanced lasers (MARBLE): a MURI program by AFOSR *(Invited Paper)*

Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

An overview of the diverse research activities under the newly funded MURI project by AFOSR will be presented. The main goal is to advance the science of radiation-balanced lasers, also known as athermal lasers, in order to mitigate the thermal degradation of the high-power laser beams. The MARBLE project involves researchers from four universities and spans research activities in rare-earth doped crystals and fibers to semiconductor disc lasers.

10121-20, Session 4

Prospects for the radiation-balanced semiconductor lasers *(Invited Paper)*

Jacob B. Khurgin, Johns Hopkins Univ. (United States)

Semiconductor gain medium is capable of delivering extraordinary large amount of power per volume but that capacity is limited by difficulty of achieving efficient heat removal using traditional cooling schemes. Using optical refrigeration can alleviate the situation and achieved radiation-balanced operating condition where all the heat generation by intraband relaxation of carriers is removed by the anti-stokes luminescence. To achieve radiation balance one needs to engineer both lasing and anti-stokes luminescence transitions, typically using reduced dimensionality gain medium, such as quantum wells and quantum dots. I this presentation I will review various pathways for achieving radiation balanced lasing in semiconductors, primarily large aperture optically pumped vertical eternal cavity surface emitting lasers (VECSEL's)

10121-21, Session 5

Candidate transverse thermoelectric materials *(Invited Paper)*

Matthew Grayson, Chuanle Zhou, Northwestern Univ. (United States)

Certain bulk semiconductor crystals are potential candidates for p ? n-type transverse thermoelectrics which hold promise for low temperature Peltier refrigeration. A p x n thermoelectric has predominantly p-type electrical conduction along one crystalline axis, and predominantly n-type electrical conduction orthogonal, and can be used to drive heat perpendicular to an applied current. To exhibit these properties, the material must be a narrow gap semiconductor with sufficiently low symmetry (non-cubic) such that the electron and hole conductivities are sufficiently different in the two directions, often due to highly anisotropic band masses that are differently-oriented. Here we identify key materials which are predicted to exhibit transverse thermoelectric behavior, and we determine various performance metrics to identify which materials will perform best for which applications and over which temperature ranges. Such metrics include the transverse figure of merit, the angle of optimal heat flow relative to the electrical current, and the angle of the applied current relative to the crystallographic axes.

10121-22, Session 5

Enhancing thermoelectric power factor at low temperatures *(Invited Paper)*

Mona Zebarjadi, Univ. of Virginia (United States)

Solid-state cooling using thermoelectric modules at low temperatures is challenging as a result of inherently low thermoelectric figure of merit (ZT) experimentally observed in different classes of materials. This talk focuses on strategies to improve the electronic part of ZT, that is, the thermoelectric power factor. At low temperatures, due to the smaller number density of phonons, electron-phonon scattering is weak. Boundary scattering and impurity scattering determine the electronic transport properties. Here, we focus on strategies to manipulate impurity scattering in order to maximize the thermoelectric power factor. These strategies include playing with the geometry of the nanoparticle dopants, using modulation-doping and surface-doping, and finally using electronic cloaking. We put emphasis on our recent hybrid organic-inorganic approach and to surface dope inorganic transport channels using different type of molecules. An algorithm will be presented to search for proper dopants and to calculate charge transfer at different levels of accuracy and complexity, starting from simplified Anderson model to complex first principles based calculations.

10121-23, Session 5

New directions in thermoelectric and thermal-electric cooling *(Invited Paper)*

Andrey Gunawan, Aravindh Rajan, David M. Rodin, Patrick Creamer, Shannon Yee, Georgia Institute of Technology (United States)

Conventional thermoelectric coolers have been widely used for cooling of electronic devices. Utilizing bismuth telluride materials, these Peltier modules are typically categorized as high heat flux devices that can achieve modest temperature differences in a compact architecture. Breaking from convention of typical steady-state thermoelectric devices, transient thermoelectrics, high powerfactor materials, and alternative methods of providing thermal-electric cooling will be discussed. While these approaches have application in electric cooling of solids, there are also wider applications including space cooling and heat pumping. Novel mechanisms and new device architectures will be presented providing inspiration for new cooling directions and materials challenges.

10121-24, Session 6

The role of interfacial disorder on thermal interface resistance *(Invited Paper)*

Joseph Feser, Univ. of Delaware (United States)

At conformal interfaces between dissimilar materials, a finite thermal resistance develops, governed by the transmission behavior of phonons. Understanding the engineering opportunities available for such interfaces thus requires an understanding of phonon transmission behavior. Due to its simplicity, the diffuse mismatch model (DMM) remains a popular description of phonon transmission across solid-solid boundaries. However, it remains unclear in which situations the DMM is good description of the underlying physics. In this talk we present theoretical and experimental observations of interfaces with tailored degrees of disorder. Using a 3-dimensional extension of the frequency domain, perfectly matched layer (FD-PML) method, we probe the validity of the diffuse mismatch model (DMM) on a mode-by-mode basis at the interface between solids with interdiffused atoms. It is found that small levels of disorder at an interface can increase the number of available modes for transmission, and subsequently reduce thermal interface resistance. These general observations are consistent with the DMM, and for submonolayer levels of interdiffusion, similar thermal interface conductance values as the DMM are seen. However, the mode-by-mode predictions of transmission coefficient vary drastically from the DMM. Particularly, (1) contrary to the fundamental assumption of the DMM, not all modes lose memory of their initial polarization and wavevector. (2) Interdiffusion in excess of a monolayer is generally found to make agreement between the DMM and the simulations worse, not better. On the other hand, experimental measurements between epitaxial and non-epitaxial versions of the same material interfaces indicate that the detailed structure of the interfaces are unimportant to the transport properties: a key result of the DMM.

10121-25, Session 6

Designing new and functionally graded materials for improved Peltier cooling *(Invited Paper)*

Eric S. Toberer, Colorado School of Mines (United States)

Advanced thermoelectric materials for electronic and optoelectronics device cooling can be discovered within the Materials Genome Initiative paradigm, while functionally grading such materials can provide further enhancements for thermoelectric cooling. Materials genome efforts are driven by a close coupling of theory, computation, and experimental validation. The implementation of a high through-put search of known and hypothetical compounds for thermoelectric performance (NSF-DMREF) has led to the identification of new classes of thermoelectric materials. Further material development involves demonstrating materials with exceptionally strong phonon-point defect scattering cross-sections. In concert with computation, general design principles for such materials emerge. Functionally graded materials can also overcome the cooling limit of traditional thermoelectric Peltier coolers by engineering a uniform thermoelectric compatibility factor at sections of the device legs that operate at different temperatures. We investigate the theoretical performance of thermoelectric coolers that maintain self-compatibility across the device and term such self-compatible coolers "Thomson coolers". Self-compatibility locally maximizes the cooler's coefficient of performance for a given figure of merit (zT) and can be achieved by adjusting the relative ratio of the thermoelectric transport properties that make up zT. A Thomson cooler requires an exponentially rising Seebeck coefficient with increasing temperature. When reasonable material property bounds are placed on the thermoelectric leg, the Thomson cooler is predicted to achieve approximately twice the maximum temperature drop of a traditional Peltier cooler with equivalent zT. We anticipate that the development of Thomson coolers will ultimately lead to solid-state cooling to cryogenic temperatures, relevant for infrared detection and laser cooling.

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10122-1, Session 1

50Gb/s PAM4 oxide VCSEL development progress at Broadcom *(Invited Paper)*

Jingyi Wang, Broadcom Ltd. (United States)

This paper will review the device design and performance of Broadcom's 50Gb/s VCSEL to enable next generation of parallel transceivers at 100 & 400 Gb/s. The VCSEL uses PAM4 advanced modulation scheme at 25-27 Gbaud. The VCSEL has been optimized for low relative intensity noise and for cleaner eyes. Preliminary wear out lifetime studies show that time to 1% failure lifetime exceed 10 years making them practical for commercial products.

10122-2, Session 1

VCSELs for optical communication at Fuji Xerox *(Invited Paper)*

Takashi Kondo, Junichiro Hayakawa, Naoki Jogan, Akemi Murakami, Jun Sakurai, Fuji Xerox Co., Ltd. (Japan); Xiaodong Gu, Fumio Koyama, Tokyo Institute of Technology (Japan)

We introduce the characteristics of vertical-cavity surface-emitting lasers (VCSELs) for use in optical communications.

In the field of optical interconnections and networks, 850-nm VCSELs are key optical transmitters due to their high-speed modulation and low power consumption. One promising candidate for achieving high-speed modulations exceeding 50 Gbps is the transverse-coupled-cavity (TCC) VCSEL. In this talk , we demonstrate the characteristics of 850-nm transverse-coupled-cavity VCSELs, which helped us achieve a high 3dB modulation bandwidth (>27 GHz) and realize eye-openings at the large-signal modulation rate of 36 Gbps. The VCSEL's epilayer structure was grown by MOCVD. The active region consists of three strained InGaAs QWs surrounded by AlGaAs barriers. The n-type and p-type DBRs are composed of AlGaAs/AlGaAs, respectively. A line-shaped H+ ion was implanted at the center of the bowtie-shaped post, dividing it into two cavities. The threshold current of the TCC VCSEL with an oxide aperture of 3.5 ?m is 0.3 mA. Only the left-hand cavity is pumped, while the right cavity is unpumped. The effect of modulation bandwidth enhancement was observed over a wide temperature range of 120K thanks to an optical feedback in the coupled cavities . This result shows the possibility of achieving high-speed VCSELs without any temperature or bias control.

We also demonstrate an ultra-compact photodetector -integrated VCSEL with two laterally-coupled cavities. The output power and photocurrent each exhibit similar tendencies under a wide range of temperature changes. This device could be used for monitoring output power without a conventional photodetector mounted separately.

10122-3, Session 1

VCSELs as light source for time-of-flight sensors

Holger Moench, Philips GmbH Photonics Aachen (Germany); Manuel Frey, Philips GmbH (Germany); Martin Grabherr, Philips GmbH U-L-M Photonics (Germany); Stephan Gronenborn, Philips Technologie GmbH (Germany); Ralph Gudde, Philips Research (Netherlands); Johanna Kolb, Philips Technologie GmbH (Germany); Michael Miller, Alexander Weigl, Philips GmbH U-L-M Photonics (Germany)

VCSELs and VCSEL arrays are used as light source for time-of-flight based sensors. The narrow emission spectrum and the ability for short pulses make them superior to LEDs. Combined with fast photodiodes or special camera chips spatial information can be obtained which is needed in diverse applications like camera autofocus, indoor navigation, 3D-object recognition or even autonomously driving vehicles.

For pulse operation at low duty cycle average heat dissipation is no longer the upper limit to the operating point of VCSELs but strong over-pulsing becomes possible. However new limits are set by electrical and reliability considerations. The paper will present details on maximum current vs. pulse length and duty cycle.

Short pulses need a good matching of driver and VCSEL assembly to get sufficient power into the chip and to minimize losses. Capacitive and inductive losses are important contributions to the energy balance beyond the classical cw power conversion efficiency. At strong over-pulsing the series resistance of conductive DBRs becomes dominant. Pulse duration sub-ns is possible by making use of gain switching but again increasing losses. Most applications need a delicate balance of maximum peak power and energy (photons) in the peak but at limited consumed energy.

The good VCSEL properties like robustness, stability over temperature and the potential for packages with integrated optics and electronics makes VCSEL sensors ideally suited for new mass applications in the consumer and automotive markets.

10122-4, Session 1

Progress in optimization of high-power high-speed VCSEL arrays

James P. Rosprim, Li Wang, Eric J. J. Martin, Preethi Dacha, Christopher J. Helms, Thomas Wilcox, Nein-Yi Li, Richard F. Carson, Mial E Warren, TriLumina Corp. (United States); James A. Lott, Technische Univ. Berlin (Germany)

Flip-chip bonding enables a unique architecture for two-dimensional arrays of VCSELs. Such arrays feature scalable power outputs and the capability to separately address sub-array regions while maintaining fast turn-on and turn-off response times. Performance of these devices is critically dependent both on the design of the VCSEL devices and the design of the sub-mount, which provides both the electrical and thermal contacts for the array. Recent results for modeling and optimization of the VCSELs and their corresponding sub-mounts will be presented.

10122-5, Session 1

Progress on high-power 808nm vertical-cavity surface-emitting lasers and applications

Delai Zhou, Jean-Francois Seurin, Guoyang Xu, Alexander Miglo, Qing Wang, Robert Van Leeuwen, Chuni L. Ghosh, Princeton Optronics, Inc. (United States)

High power 808nm semiconductor lasers are widely used for pumping a neodymium-doped yttrium aluminum garnet (Nd:YAG) crystal rod to produce high-brightness lasing at 1064nm. Such solid-state lasers have wide-spread applications across the medical, industrial, and defense fields. Vertical-cavity surface-emitting lasers (VCSELs) can emit very high power with very high power density as they can be conveniently configured into large two-dimensional arrays and modules of arrays (e.g. Seurin et al., Proc. SPIE 6908, 690808 2008). Such arrays have emerged as a promising candidate and attracted increased interests for solid-state pumping applications, due to their combined advantages of high efficiency, low diverging circular beam, narrow emission spectrum with reduced temperature sensitivity, low-cost manufacturability, simpler coupling optics, and increased reliability, especially at high temperatures.

We will discuss recent development on 808nm VCSELs for such solid-state laser pumping applications. Top emitting VCSELs were grown by MOCVD and processed into single devices and 2D arrays using selective wet oxidation process and substrate removal technique for efficient current confinement and heat removal. 50% power conversion efficiency (PCE) at 600W and 45% PCE at 800W output were achieved from 5x5mm array. Pumped with 2.3kW VCSEL arrays (peak PCE >52%, power density~3.5kW/cm2), pulse energy from Q-switched 1064nm Nd:YAG laser reached 47mJ, more than doubled from previous results.

10122-6, Session 2

Modulation enhancements for photonic crystal VCSELs

Kent D. Choquette, Stewart T. M. Fryslie, Harshil Dave, Nickolas DeNardo, Jose E. Schutt-Aine, Univ. of Illinois at Urbana-Champaign (United States); Shin Lin, Patrick J. Decker, John E. Cunningham, David K. McElfresh, Oracle (United States)

We report on modified photonic crystal vertical-cavity surface-emitting lasers that yield single-transverse mode operation at the 850 nm wavelength with reduced parasitics and improved modulation performance. Reducing the number of air holes in single-mode photonic crystal designs significantly reduces electrical and thermal parasitics while maintaining narrow spectral width emission. A graded index photonic crystal design obtained by reducing the diameter and etch depth of holes nearest the optical aperture, improves the laser modulation performance. With 3x increase in output power, endlessly single-mode emission, and demonstrated error-free transmission over 60m OM3 multi-mode fiber at a data rate of 25 Gb/s while operating at a current density of 6.6 kA/cm2, these devices are compatible for VCSEL-based data communication requiring high data rate, transmission distance product while operating within a high-reliability bias regime.

10122-7, Session 2

Continuous wave and modulation performance of 1550 nm band wafer-fused VCSELs with MBE-grown InP-based active region and GaAs-based DBRs

Andrey V. Babichev, Leonid Y. Karachinsky, Innokenty I. Novikov, Andrey G. Gladyshev, Connector Optics LLC (Russian Federation); Sergey Mikhailov, Vladimir Iakovlev, Alexei Sirbu, RTI-Research SA (Switzerland); Grzegorz Stepniak, Lukasz Chorchos, Jaroslaw Turkiewicz, Warsaw University of Technology (Poland); Mikel Agustin, Nikolay N Ledentsov, VI Systems GmbH (Germany); Kirill O Voropaev, Alexander S Ionov, OKB-Planeta PLC (Russian Federation); Anton Y. Egorov, Connector Optics LLC (Russian Federation) and ITMO Univ. (Russian Federation)

We report for the first time on wafer-fused InGaAs-InP/AlGaAs-GaAs 1550 nm vertical-cavity surface-emitting lasers (VCSELs) incorporating a InAlGaAs/InP MQWs active region with re-grown tunnel junction sandwiched between top and bottom un-doped AlGaAs/GaAs distributed Bragg reflectors (DBRs) all grown by molecular beam epitaxy. InP-based active region includes 7 compressive strained 2 nm thick quantum wells that were optimized to provide high differential gain. Devices with these active regions demonstrate lasing threshold current < 2 mA and output optical power > 2 mW in the temperature range of 20-70oC . Lasing spectra show single mode CW operation with a longitudinal side mode suppression ratio (SMSR) up to 45 dB at > 2 mW output power. Small signal modulation response of these devices shows a 3-dB modulation bandwidth of ~ 8 GHz at pump current of 9 mA and a D-factor value of 3 GHz/(mA)1/2. Achieved CW and modulation performance is quite sufficient for applications in fiber to the home (FTTH) where very large volumes of low-cost lasers are required. Compared with MOVPE, MBE grown active wafers have the advantage of superior thickness control which is important for mass production of these devices.

10122-8, Session 2

Towards a SFP+ module for WDM applications using an ultra-widely-tunable high-speed MEMS-VCSEL

Sujoy Paul, Julijan Cesar, Mohammadreza Malekizandi, Mohammad Tanvir Haidar, Technische Univ. Darmstadt (Germany); Christian Neumeyr, Markus Ortsiefer, Vertilas GmbH (Germany); Franko Küppers, Technische Univ. Darmstadt (Germany)

Vertical-cavity surface-emitting lasers (VCSELs) with microelectromechanical systems (MEMS) distributed Bragg reflector (DBR) as top mirror have attracted immense attention due to their single-mode operation and wide mode-hop free tuning range. VCSELs' very short cavity length not only enables a larger free spectral range (FSR) - which is the ultimate limit for a continuous tuning, but also allows comparatively easier integration of MEMS and other photonic components in 2-D arrays for mass fabrication. In this work, we have integrated a MEMS movable DBR onto a short-cavity high-speed VCSEL operating at 1550 nm telecom window. The wavelength tuning is realized with electro-thermal actuation of a SiOx/SiNy–based MEMS DBR. The DBR with built-in stress gradient within the dielectric layers is deposited in a low-temperature plasma-enhanced chemical vapour deposition (PECVD) chamber on a InP-based half-VCSEL by means of surface micromachining. We have demonstrated an electrically pumped MEMS tunable VCSEL with a continuous tuning of 101 nm around 1550 nm at 22 °C. With 2.6mA threshold current, the laser shows maximum CW output power of 3.2 mW at 1560 nm. The MEMS-VCSEL operates in single-mode

with SMSR > 39 dB across the entire tuning range. At 36 °C, the tuning range reaches up to 107 nm due to a cavity shrinkage. The divergence angle of the MEMS-VCSEL is approximately 5.6° for all tuning wavelengths. The intrinsic linewidth of an unpackaged device is 21 MHz. A maximum 3-dB small-signal modulation response (S21) bandwidth of 7.05 GHz is reported. Quasi-error-free operation at a record 15 Gbps using a directly modulated MEMS-VCSEL is reported for a 20 nm tuning, showing the potential of the so-called colourless source in wavelength-division multiplexed passive optical network WDM-PON applications. Together with a wavelength locker, these devices meet the standard requirements for the SFP+ modules in the tail-ends of the WDM transmission system.

10122-9, Session 2

Modeling of modulation properties of arsenide and nitride VCSELs

Michal Wasiak, Patrycja Spiewak, Lodz Univ. of Technology (Poland); Philip Moser, Technische Univ. Berlin (Germany); Marcin Gebski, Technische Univ. Berlin (Germany) and Lodz Univ. of Technology (Poland); Holger Schmeckebier, Technische Univ. Berlin (Germany); Robert P. Sarza?a, Lodz Univ. of Technology (Poland); James A. Lott, Technische Univ. Berlin (Germany)

Among various applications of arsenide vertical-cavity surface-emitting lasers (VCSELs) optical data transfer systems based on glass fibres are of a great importance. In the case of nitride VCSELs similar applications in free-space or plastic optical fibres systems can appear in the future. For a better understanding of the physical phenomena influencing the modulation properties of VCSELs, we analyzed, using our numerical models, selected contemporary constructions of arsenide and nitride VCSELs from the point of view of their behaviour under high-frequency modulation of the driving voltage. The models describe electrical, thermal and optical properties of VCSELs, as well as their capacitance and modulation properties, all as functions of the particular VCSEL epitaxial design.

Among the parameters that can be, to a certain degree, directly modified by the structure design, differential resistance, capacitance and the cavity quality factor are these which can significantly influence the modulation properties. It has been found that in the modern constructions of arsenide VCSELs designed for optical transfer applications the cavity quality factor limits the possible modulation frequencies stronger than the electrical phenomena. In contrastthe existing nitride VCSELs are not designed for applications requiring high-frequency modulation. In these constructions, their resistance and capacitance seem to be the main factor limitting the frequency of modulation.

10122-10, Session 2

Buried tunnel junction 850-nm VCSEL for reliability and wafer uniformity

Ping-Show Wong, Jingzhou Yan, TaChung Wu, James J. Pao, Majid Riaziat, OEpic Semiconductors Inc. (United States)

We are reporting the first fabrication of an 850nm buried tunnel junction (BTJ) VCSEL. The BTJ has been widely implemented in a variety of VCSEL structures but not for short wavelength (<0.9 um) devices.

Buried tunnel junction (BTJ) VCSELs promise significant performance advantages over oxide aperture VCSELs. To name a few: (1) higher emission uniformity can be attained over large-area VCSEL arrays; (2) small-aperture devices can be fabricated more reproducibly; (3) devices are expected to have higher reliability since there is no strained oxide layer within the semiconductor matrix; (3) the majority of the p-side DBR layers are converted to n-doped materials resulting in lower electrical resistance of the DBR and lower free carrier absorption.

To design a tunnel junction for 850nm VCSELs we considered multiple parameters. First, in order to achieve abrupt junctions, we had to work with n-type dopants other than silicon. Second, we had to minimize free carrier absorption due to highly doped n+/p+ layers needed for low resistivity. Finally, we had to select a proper layer thickness, and to ensure compatibility with the regorwth of n-doped materials and other VCSEL fabrication processes. In this paper, we report the successful fabrication and performance of 850-nm BTJ VCSELs and we present a comparison of tunnel junctions with GaAs, AlGaAs and InGaP materials with various dopants. Key achieved parameters include a significant improvement of the slope efficiency from approximately 0.45 W/A in an oxide VCSEL to over 0.6 W/A.

Acknowledgement

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10122-11, Session 2

Comparative study of contact geometry for bottom-emitting 980-nm VCSELs

Ricardo Rosales, Holger Schmeckebier, Constanze Boldt, Philip Moser, Technische Univ. Berlin (Germany); Mial E. Warren, Richard F. Carson, TriLumina Corp. (United States); James A. Lott, Technische Univ. Berlin (Germany)

Substrate-emitting GaAs based oxide-confined 980-nm vertical-cavity surface-emitting lasers (VCSELs) with top-surface high-frequency ground-source-ground contact pads are designed, fabricated, and characterized. The devices are composed of standard top and bottom epitaxially-grown AlGaAs distributed Bragg reflectors (DBRs). The top DBR is capped with p-contact metal for uniform current injection and laser emission through the GaAs substrate. The devices are realized on a single epitaxial wafer with n-ohmic-contacts placed on a thick (n+)GaAs buffer layer beneath the bottom (n)DBR and alternatively with the n-ohmic-contacts placed on an (n)GaAs intra-cavity layer lying within the bottom (n)DBR. Static device parameters including threshold and rollover current, differential resistance, peak output power, and wall-plug efficiency are extracted for VCSELs with oxide-aperture diameters ranging from 3 to 12-μm and at different temperatures. At room temperature threshold currents are achieved from the sub-mA range up to about 3.5-mA with maximum output powers exceeding 12-mW. Increasing the temperature up to 85 °C slightly increases the threshold current while the peak output power is about halved. The differential resistance at the thermal rollover current is comparable for standard and intra-cavity n-metal-contacts. Small-signal analysis is performed for different bias currents, temperatures, oxide-aperture diameters, and n-contact types. Under optimal bias conditions the 3-dB bandwidth exceeds 15 GHz. Direct current modulation-based on-off keying signal generation is investigated from 10 to 40-Gb/s. The influence of an anti-reflection-coated substrate, a thinned substrate, and the combination of both is investigated and discussed.

10122-12, Session 2

Rapid fabrication and characterisation techniques for VCSELs

Lewis Kastein, Cardiff Univ. (United Kingdom) and IQE (United Kingdom); Peter M. Smowton, Cardiff Univ. (United Kingdom); Graham Clarke, IQE (United Kingdom)

Reliable and rapid test structure fabrication and characterisation techniques are required in a high volume production environment to assess material quality and suitability for end product applications. As materials and growth techniques continue to evolve an increasing number of methods are required to investigate the relationship between layer design, material growth and device performance. Reliability, speed and the cost-effectiveness of these techniques are key considerations.

Simple production techniques exist to examine the emission spectrum of VCSEL material in the direction of the lasing cavity. This work investigates an ultra-fast method to obtain detail of the active region emission wavelength independent of the distributed Bragg mirror stack by examining the electronic structure of the material.

Rather than directly observing light emission perpendicular to the lasing direction, which can result in a convolution of the emission and absorption spectrum, a technique that measures a photo-voltage spectrum by illuminating the edge of the wafer (perpendicular to the lasing direction) is employed. Illumination in this configuration can also allow information regarding the strain of the quantum wells to be determined. This technique requires very few fabrication steps and is highly cost effective. Rapid techniques to fabricate VCSEL test structures for comparison between material characteristics and device performance are also investigated.

10122-13, Session 3

VCSEL modal dynamics and implications for 100Gbps links *(Invited Paper)*

Stephen E. Ralph, Justin Lavrencik, Georgia Institute of Technology (United States)

No Abstract Available.

10122-14, Session 3

Single-mode 850-nm vertical-cavity surface-emitting lasers with Zn-diffusion and oxide-relief apertures for > 50 Gbit/sec OOK and 4-PAM transmission *(Invited Paper)*

Jin-Wei Shi, National Central Univ. (Taiwan); Chia-Chien Wei, National Sun Yat-Sen Univ. (Taiwan); Jyehong Chen, National Chiao Tung Univ. (Taiwan); Nikolay Ledentsov, VI Systems GmbH (Germany); Ying-Jay Yang, National Taiwan Univ. (Taiwan)

Vertical-cavity surface-emitting lasers (VCSELs) has become the most important light source in the booming market of short-reach (< 300 meters) optical interconnect (OI). The next generation OI has been targeted at 56Gbit/sec data rate per channel (CEI-56G). However, the serious modal dispersion of multi-mode fiber (MMF), limited speed of VCSEL, and its high resistance (> 150Ohm) seriously limits the >50 Gbit/sec linking distance (< 10m) by using on-off keying (OOK) modulation scheme without any signal processing techniques. In contrast to OOK, 4-PAM modulation format is attractive for >50 Gbit/sec transmission due to that it can save one-half of the required bandwidth. Nevertheless, the power penalty and the linearity of transmitter would become issues in the 4-PAM linking.

Besides, in the modern OI system, the optics module must be packaged as close as possible with the integrated circuits (ICs). The heat generated from ICs will degrade the speed of VSCEL. Here, we review our recent work about 850 nm VCSEL, which has unique Zn-diffusion/oxide-relief apertures and special p-doping active layer with strong wavelength detuning to further enhance its modulation speed and high-temperature (85?) performances. Single-mode (SM) devices with high-speed (~26GHz), reasonable resistance (~70 Ohm and moderate output power (~1.5mW) can be achieved. Error-free 54Gbit/sec OOK transmission through 1km MMF has been realized by using such SM device. Besides, the volterra nonlinear equalizer has been applied in our 4-PAM 64 Gbit/sec transmission through 100 meter MMF, which significantly enhance the linearity of device and outperforms fed forward equalization (FFE) technique.

10122-15, Session 3

High-speed optical interconnects with 850-nm VCSELS and advanced modulation formats *(Invited Paper)*

Krzysztof Szczerba, Tamas Lengyel, Zhongxia He, Jingjing Chen, Peter A. Andrekson, Magnus Karlsson, Herbert Zirath, Anders G. Larsson, Chalmers Univ. of Technology (Sweden)

Data rates of 100 Gbps using a single 850 nm VCSEL are enabled by 4 PAM, pre-emphasis and post-equalization. Multilevel modulation puts however stringent requirements on the VCSEL performance. VCSELs with more damping, and thus flatter frequency response, but still high modulation bandwidth are shown to perform better. Multilevel modulation requires higher signal to noise ratio at the receiver, which means that higher output power and low relative intensity noise (RIN) are necessary because RIN becomes a limiting factor at high received optical power levels and causes error floors. The error floors can be lowered by the application of a forward error correction, but this increases latency and it is acceptable only in some applications. In our contribution we present results of our investigation on VCSEL designs optimized for high-speed operation with multi-level modulation.

The effect of the increased output power requirements on the system energy efficiency is shown. We show that while low VCSEL oxide aperture sizes enable very high modulation bandwidth at very low bias currents, and consequently low energy per bit, after including the system requirements the VCSEL energy consumption per bit becomes linearly dependent on the optical out power requirements. The power requirements are propagated further into the VCSEL driver. It enables however system-wide energy consumption optimization, including the VCSEL, driver, receiver and possibly the error correction circuits. We present also new InP VCSEL drivers suitable for multilevel PAM transmission at high speed and low energy consumption.

10122-16, Session 4

Hybrid vertical-cavity laser integration on silicon *(Invited Paper)*

Emanuel P. Haglund, Chalmers Univ. of Technology (Sweden); Sulakshna Kumari, IMEC (Belgium); Johan S. Gustavsson, Erik Haglund, Chalmers Univ. of Technology (Sweden); Gunther Roelkens, Roel G. Baets, IMEC (Belgium); Anders G. Larsson, Chalmers Univ. of Technology (Sweden)

Integration of light sources on silicon enables fully integrated silicon photonic circuits with a high degree of functionality and performance complexity for various applications. Among the possible light source integration technologies, the hybrid vertical-cavity laser by heterogeneous integration is attractive as it has the potential for low drive current, high efficiency, and small footprint. Coupling to an in-plane waveguide can be accomplished by e.g. an intra-cavity waveguide with a weak diffraction grating.

We have developed a technology for hybrid-cavity VCSEL (HC-VCSEL) integration where a GaAs-based half-VCSEL is attached to a dielectric distributed Bragg reflector on silicon by adhesive bonding. While the device does not yet contain elements for coupling to an in-plane waveguide it lends itself to the development and implementation of the integration concept.

HC-VCSELs at 850 nm with sub-mA threshold current, >2 mW output power, and 25 Gbit/s modulation speed are demonstrated. In addition, the thickness of the bonding interface can be used to optimize a certain performance parameter at a given temperature or to minimize the variation of performance over temperature.

Integration of such short-wavelength light sources on a silicon-nitride waveguide platform on silicon will enable fully integrated silicon photonic

circuits for applications in life science, bio-photonics, and short-reach optical interconnects.

10122-17, Session 4

Wavelength-swept VCSEL *(Invited Paper)*

Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

We review recent progress of monolithic, wavelength-swept vertical-cavity surface-emitting lasers (VCSELs) and their applications. A typical electrically-pumped VCSEL consists of two oppositely doped distributed Bragg reflectors (DBRs) with a cavity layer in between. In the center of the cavity layer resides an active region, consisting of multiple quantum wells. Due to the short cavity length which results in a very large longitudinal mode spacing, there is only one longitudinal mode that lases. Lasing wavelength can be continuously swept by varying the cavity length. The first generation of sweptable tunable VCSELs were demonstrated with part or entire top DBR be held by a micro-electro-mechanical structure (MEMS) and the lasing wavelength is varied by moving the MEMS with an electric bias. Electrically-pumped, tunable VCSELs emitting at 850-nm, 940-nm, 1060-nm, 1300-nm and 1550-nm were all demonstrated. These VCSELs are demonstrated with high modulation rate and coherent lengths, well poised for optical communications applications in datacenters, fiber-to-the-home and metropolitan area networks. In addition, new applications in optical coherence tomography and LIDAR are particular interesting for continuously tunable VCSEL.

10122-18, Session 4

Intracavity and extracavity-contacted 980-nm oxide-confined VCSELs for optical interconnects and integration *(Invited Paper)*

Philip Moser, Holger Schmeckebier, Technische Univ. Berlin (Germany); Marcin Gebski, Technische Univ. Berlin (Germany) and Lodz Univ. of Technology (Poland); Patrycja Spiewak, Lodz Univ. of Technology (Poland); Kilian Moser, Technische Univ. Berlin (Germany); Michal Wasiak, Lodz Univ. of Technology (Poland); James A. Lott, Technische Univ. Berlin (Germany)

Intense research in the last years has finally led to room-temperature 30 GHz modulation bandwidths of directly and 37 GHz bandwidth of indirectly modulated VCSELs and VCSEL arrays. While the bandwidth improvements appear to slowly saturate, one next big challenge is to make VCSELs viable for integration onto silicon without drawbacks on the modulation bandwidth. Various integration schemes of VCSELs might require intra-cavity contacts, bottom emission, complete or partial replacement of semiconductor DBRs with grating reflectors or dielectric DBRs or any combination of these processing variations, as well as lifting-off the VCSELs from the host substrate. We present directly modulated oxide-confined top-emitting 980-nm VCSELs processed from one single epitaxial wafer design into four different extra- and intra-cavity contact variations. The impact of the different contact schemes on the static and dynamic VCSEL properties is demonstrated and evaluated experimentally for VCSELs with different oxide-aperture diameters and at different ambient temperatures. Differences in current flow and differential resistance for these contact variations are investigated via modelling and the potential for improving our intra-cavity VCSELs is discussed. We end the talk by reviewing our recent work on bottom-emitters and VCSELs with hybrid semiconductor/dieletric DBRs.

10122-19, Session 5

Temperature-robustness of single-mode vertical-cavity surface-emitting lasers with engineered leakage of high-order transverse optical modes

Vitaly A. Shchukin, Nikolay Ledentsov Jr., Vladimir Kalosha, Joerg-Reinhardt Kropp, Nikolay Ledentsov, VI Systems GmbH (Germany)

Approaches known earlier in technology of vertical–cavity surface–emitting lasers (VCSELs), such as: oxide confined apertures, apertures applying oxide relief technology forming air gaps, apertures based on Zn–diffusion–induced alloy composition intermixing of Ga(1–x)Al(x)As–based distributed Bragg reflectors (DBRs), allow efficient engineering of the matching optical modes in the regions inside and outside the VCSEL aperture [1–4]. Each of this approaches results in the formation of i) a core region of the VCSEL through which current flows and optical modes are generated and ii) a periphery region containing oxide layers or air gaps or intermixed DBRs. These two regions have distinct vertical refractive index profiles which can be engineered such that they promote leakage of the transverse optical modes from the core region to the selectively oxidized [1–3], or selectively intermixed [4] periphery of the device. The reason of the leakage is that the VCSEL modes in the core can be coupled to tilted modes in the periphery if the orthogonality between the core mode and the modes at the periphery is broken by the optical field redistribution between the inner and outer VCSEL aperture regions. Three–dimensional modeling reveals that significantly stronger leakage losses can be realized for high–order transverse modes than that of the fundamental one, as high–order modes have a higher field intensity close to the oxide layers or intermixed region. Experimental 850–nm GaAlAs leaky VCSELs produced in the modeled design demonstrate single–mode lasing with the aperture diameters up to 5um with side mode suppression ratio >20dB at the current density of 10kA/cm^2 [1–3]. However, the leakage strength was shown to oscillate strongly with the VCSEL aperture diameter causing a reversal of the mode selectivity in a narrow range of oxide aperture diameters [1], the effect not observed experimentally. The experiment also shows that at very high current densities at moderate aperture diameters high order modes evolve and may dominate the spectra for the devices having a stable single mode operation at lower currents.The In the present paper self–consistent three–dimensional modeling of the optical modes in a 850 nm–VCSEL including electric current and temperature distribution has been carried out. The results illustrate the impact of the temperature–induced effects on optical modes which may strongly affect (both improve and degrade) the mode selectivity by applying proper design adjustments.

[1] V. Shchukin, et al., IEEE J. Quant. Electron. vol. 50, pp. 990–995 (2014)

[2] V. Shchukin, et al., SPIE Proc. vol. 9381, paper 93810V (2015)

[3] N. Ledentsov, Jr., et al., IEEE J. Quant. Electron. vol. 52, p. 2400207 (2016)

[4] N. Ledentsov, Jr., et al., IEEE J. Quant. Electron. vol. 52, p. 2400406 (2016)

10122-20, Session 5

Transverse mode control in proton-implanted and oxide-confined VCSELs via patterned dielectric anti-phase filters

Benjamin Kesler, Thomas O'Brien, John M. Dallesasse, Univ. of Illinois at Urbana-Champaign (United States)

A novel method for controlling the transverse lasing modes in both proton implanted and oxide-confined vertical-cavity surface-emitting lasers (VCSELs) with a multi-layer, patterned, dielectric anti-phase filter is presented. Using a simple photolithographic liftoff process, dielectric layers are deposited and patterned on individual VCSELs to modify (increase or

decrease) the mirror reflectivity across the emission aperture via anti-phase reflections, creating spatially-dependent threshold material gain. The shape of the dielectric pattern can be tailored to overlap with specific transverse VCSEL modes or subsets of transverse modes to either facilitate or inhibit lasing by decreasing or increasing, respectively, the threshold modal gain. A silicon dioxide (SiO2) and titanium dioxide (TiO2) anti-phase filter is used to achieve a single-fundamental-mode, continuous-wave output power greater than 4.0 mW in an oxide-confined VCSEL at a lasing wavelength of 850 nm. A filter consisting of SiO2 and TiO2 is used to facilitate injection-current-insensitive fundamental mode and lower order mode lasing in proton implanted VCSELs at a lasing wavelength of 850 nm. Higher refractive index dielectric materials such as amorphous silicon (a-Si) are used to increase the effectiveness of the anti-phase filter on proton implanted devices by reducing the threshold modal gain of any spatially overlapping modes. This additive, non-destructive method allows for mode selection at any lasing wavelength and for any VCSEL layer structure without the need for semiconductor etching or epitaxial regrowth. It also offers the capability of designing a filter based upon available optical coating materials.

10122-21, Session 5

Metallic monolithic high-contrast grating VCSELs: new concept of vertical current injection

Tomasz G. Czyszanowski, Marcin Gebski, Maciej Dems, Lodz Univ. of Technology (Poland); Krassimir Panajotov, Vrije Univ. Brussel (Belgium)

Monolithic high contrast gratings (MHCGs) can be implemented in any material with a real refractive index larger than 1.75 without the need of the combination of low and high refractive index materials. It has a great application potential in passive and active optoelectronic devices, but mostly it has great prospects in application to monolithically integrated phosphide and nitride-based Vertical-Cavity Surface-Emitting Lasers (VCSELs) that lack a pair of lattice-matched semiconductor materials of high refractive index contrast. Incorporation of MHCG can lead to simplification of VCSEL design. In the extreme design VCSEL can be reduced to the active region with vertical carrier confinement scheme sandwiched between MHCG mirrors etched on both surfaces in post processing. MHCG VCSELs however require lateral current confinement to minimize light absorption and maximize light emission hence contacts must be implemented out of VCSEL's axis. We propose MHCG integrated with metallic stripes which can be implemented in the VCSEL axis, facilitating high optical power reflectance, perfectly vertical current injection, allows elimination of the inbuilt current confinement and scaling of emitted power by simple variation of metallic MHCG spatial dimensions. To give the credibility to proposed design we perform numerical analysis of VCSEL with metallic MHCG using self-consistent model of optical, electrical and thermal phenomena. We discuss characteristics of the proposed designs realized in numerous possible materials.

10122-22, Session 5

Transverse mode selection in vertical-cavity surface-emitting lasers via deep impurity-induced disordering

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Top emission 850-nm vertical cavity surface emitting lasers (VCSELs) demonstrating transverse mode selection using impurity-induced disordering via zinc diffusion are presented. The intermixing of the distributed mirrors reduces the reflectivity of the DBR stack for higher order modes while leaving the fundamental lasing mode relatively unperturbed. In addition, higher order modes experience an increase in non-radiative recombination due to the increase of free carrier absorption from the p-type zinc impurities. The relative contributions of these two mechanisms to the total loss experienced by higher order modes is shown to be controlled by the conditions under which the layers are disordered. The diffusion also reduces contact and series resistances and provides a more efficient current injection path to the active region of the device by smoothing hetero-interfaces in the diffused region. A simple model based on the intermixing of Group III elements during zinc diffusion is presented as well to describe the difference in lasing threshold and resonant wavelength between diffused and undiffused VCSELs. In addition, the optimal ratio of zinc-diffused emission aperture to oxide aperture is studied to maximize both output power and higher order mode suppression. Special attention is given to the lateral diffusion along the dielectric-semiconductor boundary and the difference in diffusion rates of zinc in high aluminum content layers which cause a controllably tapered emission aperture. Finally, polarization control in elliptical VCSELs with impurity-induced disordering is studied by varying the fraction of the major axis that is disordered.

10122-23, Session 5

Investigations on polarization oscillation amplitudes in spin-VCSELs

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Compared to conventional vertical-cavity surface-emitting lasers (VCSELs), spin-pumped VCSELs offer the possibility of polarization control and fast polarization dynamics. It has been demonstrated that oscillations in the circular polarization degree can be excited. In short, the frequency of these polarization oscillations is determined by the frequency splitting between the two orthogonal linearly polarized cavity modes and therefore by the cavity birefringence. The polarization oscillation frequency is the resonance frequency of the VCSEL's polarization dynamics and can be compared to the conventional resonance frequency for intensity modulation. We have demonstrated polarization oscillations up to 44 GHz, exceeding the direct intensity resonance frequency in the investigated devices by far. As the polarization oscillation frequency can be increased by increasing the cavity birefringence and a VCSEL cavity birefringence of more than 250 GHz has been demonstrated, using polarization dynamics is a possible way of substantially increasing the modulation speeds of VCSELs, which is for instance interesting for high-bandwith short-haul optical interconnects. The experimental results associated with the polarization oscillation effects can be simulated by the widely used spin-flip model. In this work we focus on the amplitude of the polarization oscillations. Previous publications have shown a decrease with increasing oscillation frequency. Here, we show amplitude dependencies on several system parameters like the photon, spin and carrier lifetimes as well as pumping conditions. Based on this, we investigate how to increase the polarization oscillation amplitude, since a significant amplitude is necessary for, e.g., data transmission applications.

10122-24, Session 5

Correlation between polarization modes in VCSEL with optical feedback

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Vertical-cavity surface-emitting laser (VCSEL) dynamics has emerged as a highly attractive field of research for numerous applications such as high-speed telecommunication and sensing. In addition, VCSELs are known

to exhibit interesting new physics related to polarization competition : although the light emitted at threshold is typically linearly polarized, increasing the driving current may lead to polarization switching and even polarization instabilities including deterministic polarization chaos. In this work, we bring experimentally and numerically new light into the polarization dynamics of a VCSEL with optical feedback and re-visit earlier predictions.

Similar to edge-emitting lasers (EEL), VCSELs subjected to optical feedback can exhibit erratic fluctuations of their optical power at slow and fast time scales in the well-known low-frequency fluctuations (LFF) regime. The peculiarity of LFF in VCSELs is that two types of LFFs (Type I and II) can be observed depending on the polarization mode competition. In Type-I, the two modes are correlated at the average LFF frequency while they are anti-correlated in LFF Type-II. We show that those correlation properties of VCSEL with optical feedback at low frequency greatly influence the correlation at the external-cavity frequency. We also bring the first in-depth explanation to the peculiar observation of a double-peak structure close to the external-cavity frequency in the power spectrum of laser diodes with feedback (VCSEL and EEL). We show that this double-peak structure is related to the system trajectory in the phase space around ruins of external-cavity modes and antimodes by a “push and pull” motion.

10123-1, Session 1

Dilute bismide III-V alloys for efficient infrared lasers and detectors *(Invited Paper)*

Eoin O'Reilly, Tyndall National Institute (Ireland) and Univ. College Cork (Ireland); Christopher A. Broderick, Univ. of Bristol (United Kingdom); Peter Ludewig, Wolfgang Stolz, Kerstin Volz, Philipps-Univ. Marburg (Germany); Judy M. Rorison, Univ. College Cork (Ireland); Shirong Jin, Igor P. Marko, Stephen J. Sweeney, Univ. of Surrey (United Kingdom)

We overview that the incorporation of bismuth into III-V alloys brings several advantages for device applications, including i) Strong control of the band gap energy from near-infrared through to mid-infrared on commercially standard substrates such as GaAs and InP; ii) Extremely high spin-orbit splitting energies which can be exploited to produce temperature insensitive lasers, and efficient absorption for mid-infrared photodetectors; and iii) Fine control of the band offsets. A theoretical and experimental analysis is presented of the gain characteristics of GaBiAs/GaAlAs quantum well lasers with 2% Bi and the wider potential of this novel alloy for wider applications is discussed.

The growth of highly mismatched dilute bismide and nitride alloys can have a profound effect on the properties of III-V semiconductors, bringing a number of advantages for device applications, including:

• Strong control of the band gap energy from near-infrared through to mid-infrared and even zero gap whilst remaining lattice-matched to standard substrates such as GaAs, InP and Ge;

• Extremely high spin-orbit splitting energies which can be exploited to produce temperature insensitive lasers, and efficient absorption for mid-infrared photodetectors;

• Fine control of the conduction and valence band offsets which provides a means to eliminate carrier leakage effects in mid-infrared lasers and to control carrier escape in photodetector and photovoltaic devices.

Considerable progress has been made in the growth of dilute bismide alloys, including the demonstration of electrically pumped room temperature GaBiAs/AlGaAs quantum well (QW) lasers grown on GaAs. We modify the conventional 8-band k.p model, including 4 extra states in a 12-band model to describe the effects of Bi resonant defect states on the valence band structure of GaBiAs, We show that this 12-band model provides an excellent description of GaBiAs materials investigated to date and also of the gain characteristics of existing GaBiAs/AlGaAs QW lasers, with 2% Bi in the QWs. Further theoretical analysis shows that Auger-free 1.5 μm laser emission can be achieved with 13% Bi QWs grown on a GaAs substrate, with mid-IR (2.5-4 μm) emission possible on InP using 5-7% Bi QWs. Finally, we briefly overview the potential of dilute bismide-nitride alloys for wider optoelectronic device applications.

10123-2, Session 1

Optical gain in GaAsBi-based quantum-well diode lasers

Igor P. Marko, Univ. of Surrey (United Kingdom); Christopher A. Broderick, Univ. of Bristol (United Kingdom); Shirong Jin, Univ. of Surrey (United Kingdom); Peter Ludewig, Wolfgang Stolz, Kerstin Volz, Philipps-Univ. Marburg (Germany); Judy M. Rorison, Univ. of Bristol (United Kingdom); Eoin P. O'Reilly, Tyndall National Institute (Ireland); Stephen J. Sweeney, Univ. of Surrey (United Kingdom)

GaAsBi offers the possibility to develop near-IR semiconductor lasers such that the spin-orbit-split-off energy (?SO) is greater than the bandgap (Eg) in the active region with lasing wavelengths in the datacom/telecom range of 1.3-1.6 μm. This promises to suppress the dominant efficiency-limiting loss processes as Auger recombination, involving the generation of "hot" holes in the spin-orbit split-off band (the so-called "CHSH" process), and inter-valence band absorption (IVBA), where emitted photons are re-absorbed in the active region, thereby increasing the internal optical losses and negatively impacting upon the laser characteristics being responsible for the main energy consumption. In addition to growth and fabrication processes refinement, a key aspect of efforts to continue the advancement of the GaAsBi material system for laser applications is to develop a quantitative understanding of the impact of Bi on key device parameters. In this work, we present the first experimental measurements of the absorption, spontaneous emission, and optical gain spectra of GaAsBi/AlGaAs QW lasers using a segmented contact method and a theoretical analysis of these devices, which shows good quantitative agreement with the experiment. Internal optical losses of 10-15 cm-1 and peak modal gain of 24 cm-1 are measured at threshold and a peak material gain is estimated to be 1500 cm-1 at current density of 2 kA/cm-2, which agrees well with the calculated value of 1560 cm-1. The theoretical calculations also enabled us to identify and quantify Bi composition variations across the wafer and Bi-induced inhomogeneous broadening of the optical spectra.

10123-3, Session 1

Strain-compensated Ga(AsP)/Ga(AsBi)/Ga(AsP) quantum-well active-region lasers

Honghyuk Kim, Yingxin Guan, Kamran Forghani, Thomas F. Kuech, Luke J. Mawst, Univ. of Wisconsin-Madison (United States)

Ga(AsBi) quantum well (QW) active regions are an alternate to dilute-nitride QWs for achieving lasers in the telecom wavelength regions (?~1.3-1.55?m) on GaAs substrates. Ludewig et al first reported the successful operation of Ga(AsBi) single quantum well laser in 2013 [1] with low threshold current densities, Jth=1.56kA/cm2 where (AlGa)As was used as a barrier material for low Bi-content QWs to improve the electron confinement in the conduction band and reduce thermally activated carrier leakage from the QW. We implement here the use of tensile-strained Ga(AsP) as a QW barrier material, providing carrier confinement as well as potential for strain-balancing. Laser structures employing a single GaAs0.976Bi0.024 quantum well (SQW) with either GaAs0.8P0.2, Al0.15Ga0.85As, or GaAs barrier materials were grown by MOVPE on a nominally singular (001) GaAs substrate Ridge waveguide lasers, 25?m-wide and 1mm-long ridge, were fabricated and characterized under pulsed current conditions. The threshold current densities for devices are 5.9kA/cm2 and 5.8kA/cm2 for GaAsP barriers and Al0.15Ga0.85As barriers respectively, with a lasing wavelength of 960nm. Devices with GaAs barriers only lased at higher currents for a short wavelength transition ~900nm. While threshold currents are relatively high, no post growth thermal annealing was performed on these laser materials. Thermal annealing studies will be presented indicating significant improvement in QW luminescence and reduction in Jth can be achieved after the post-growth in-situ annealing.

[1] Ludewig, P., Knaub, N., Hossain, N., Reinhard, S., Nattermann, L., Marko, I. P., and Volz, K. 2013. Appl. Phys. Lett., 102(24), 242115.

10123-4, Session 1

Quantum-dot lasers with asymmetric barrier layers: a path to ideal performance

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To overcome the limitations placed on the operating characteristics of diode lasers by recombination outside their active region, two novel designs were proposed for them: one using double tunneling-injection (injection of both electrons and holes) into the active region, and the other using two asymmetric barrier layers (ABLs) flanking the active region. The barrier layers are asymmetric in that they have considerably different heights for the carriers of opposite signs. The ABL located on the electron- (hole-) injecting side of the structure provides a low barrier (ideally no barrier) for electrons (holes) [so that it does not prevent electrons (holes) from easily approaching the active region] and a high barrier for holes (electrons) [so that holes (electrons) injected from the opposite side of the structure do not overcome it]. The use of ABLs should thus ideally prevent the simultaneous existence of electrons and holes (and hence parasitic electron-hole recombination) outside the active region. In this work, we calculate the threshold and power characteristics of quantum dot lasers with ABLs. We show that quantum dot lasers with ABLs offer close-to-ideal performance: low threshold current density, very high characteristic temperature (virtually temperature-independent operation), close-to-unity internal differential quantum efficiency, and linear light-current characteristic.

10123-5, Session 1

High-bandwidth temperature-stable 1.55-um quantum-dot lasers *(Invited Paper)*

Johann P. Reithmaier, Univ. Kassel (Germany); Gadi Eisenstein, Technion-Israel Institute of Technology (Israel)

In the last decade, semiconductor quantum dot (QD) structures have attracted major interest from both fundamental physics and potential optoelectronic device applications. Of special significance are QD lasers operating at 1.55 μm due to their potential role in optical fiber communication. Self-assembled semiconductor QDs formed via the Stranski-Krastanov (SK) growth mode have made possible an active medium with unique properties for optoelectronic devices such as laser diodes and light-emitting diodes. For laser applications, it is necessary to establish a high QD density with a homogenous size distribution and preferably a round-shaped geometry. This results in device related properties such as high temperature stability, reduced threshold current and increased spectral and differential gain, all of which lead to high modulation bandwidths.

An overview is given about the recent improvement in 1.55-μm QD lasers for direct modulation. Based on improved QD epitaxy,1 record values in small-signal modulation bandwidth of more than 15 GHz and in digital modulation of up to 35 GBit/s were obtained.2 Due to the high modal gain and robust ground-state transition, the temperature dependence of the laser performance could be very much improved with characteristic temperatures of T0 = 125K and T1 near to 400K.3 This allow a temperature stable modulation bandwidth between 15-60°C of (14 +/- 1)GHz sufficient for 25 GBit/s digital modulation for the whole temperature range.2

[1] S. Banyoudeh et al., JCG 425, 299 (2015).

[2] S. Banyoudeh et al., appears in PTL (2016).

[3] S. Banyoudeh et al., Photonics West, Proc. SPIE 97670I (March, 2016).

10123-6, Session 2

Advances in semipolar InGaN laser diodes *(Invited Paper)*

Mel McLaurin, James Raring, Christiane Poblenz, Paul Rudy, Georg Aigeldinger, Eric Goutain, Hua Huang, Soraa Laser Diode, Inc. (United States)

We present state-of-the-art performance from laser based light sources based on semipolar GaN. Recent advances toward the commercialization of blue, InGaN semipolar laser diodes are described. Additionally, we introduce next generation white light sources based on laser-pumped phosphor architectures.

10123-7, Session 2

Analysis of waveguide architectures of InGaN/GaN diode lasers by nearfield optical microscopy

Sebastian Friede, Jens Wolfgang W. Tomm, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Sergei Kühn, Max-Born-Institut (Germany); Veit Hoffmann, Hans Wenzel, Ferdinand-Braun-Institut (Germany)

Waveguide (WG) architectures of 420-nm emitting InGaN/GaN diode lasers are analyzed by photoluminescence (PL) and photocurrent (PC) spectroscopy using a nearfield scanning optical microscope as excitation and detection device. The measurements with a spatial resolution of ~100 nm are implemented just by scanning the fiber tip along the unprepared front facets of the devices. PL is collected by the fiber tip, whereas PCs are extracted from the contacts that are anyway present for power supply. The components of the 'optical active cavity', multiple quantum wells (MQW), WGs, and cladding layers are separately inspected. Even separate analysis of p- and n-sections of the WG (left and right of the MQW) became possible. Defect levels are detected in the p-part of the WG. Their presence is consistent with the Mg-doping. Moreover, we show that during epitaxial growth, the homogeneity of the n-WG section directly affects the homogeneity of the MQW layers that are grown on top of the n-WG. An increased efficiency of carrier capture into InGaN/GaN WGs compared to GaN WGs is observed. Thus InGaN/GaN WGs provide electrical confinement, as well. NSOM PL and PC at GaN-based devices do not reach the clarity and spatial resolution for WG mode analysis as seen before for GaAs-based devices. This is due to the high modal absorption. Thus, NSOM based optical analysis turns out to be an efficient tool for analysis of single layers grown into InGaN/GaN diode laser structures, even if this analysis is done at a packaged ready-to-work device.

10123-8, Session 2

How the interface affects Auger process in quantum wells

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InGaN quantum well (QW) devices have been extensively studied for light emitting diodes and laser applications in recent decades. Recent work showed the Auger recombination process as one of the important efficiency-limiting factors in the InGaN devices, but the discrepancies between the reported theoretical and experimental Auger coefficient values remain unexplained. Recent findings indicated the existence of interface roughness ranging from one to six monolayers in the InGaN QW, but the effect on the Auger recombination process is still unknown up to present.

Previous work demonstrated that the interface roughness adversely affects the photoluminescence lineshape in the semiconductor QW laser. Since the theoretical investigations on the evaluation of Auger recombination processes commonly assume sharp interface between QW and barrier, the accuracy in the estimation of Auger coefficient values could potentially be improved by incorporating the roughness effect. Thus, evaluating the Auger recombination process by including the interface roughness factor is a critical step towards providing enhanced understanding of Auger mechanisms in InGaN QW devices.

In this work we developed the calculation approach and numerical model of calculating the Auger recombination process that takes into account the interface roughness effect in the InGaN QW. The Auger recombination coefficients of InGaN QW with varying degrees of interface roughness are analyzed. Specifically, our findings indicate significant interface roughness effect in thin InGaN QW as compared to thick InGaN QW. In addition, a comparison of the Auger rates in InGaN QW with various thickness will be discussed in details.

10123-9, Session 2

GaInN laser diodes from 440 to 530nm: a performance study on single-mode and multi-mode R&D designs *(Invited Paper)*

Uwe Strauss, Andre Somers, Urs Heine, Teresa Wurm, Matthias Peter, Christoph Eichler, Sven Gerhard, Georg Bruederl, Soenke Tautz, Bernhard Stojetz, Andreas Loeffler, Harald Koenig, OSRAM Opto Semiconductors GmbH (Germany)

The range of applications of blue and green lasers are increasing from year to year. Driving factors are costs and performance. On one hand side we study the performance of low power single mode R&D laser structures with Gaussian beam profile: efficiencies range from 8% (green) to 25% (blue). On the other hand we present results on broad area multi-mode R&D designs for multi Watt power levels with efficiencies from 15% (green) to 40% (blue). Successful devices also need reliabilities. Therefore we study power degradation as well as facet stabilities.

10123-10, Session 2

High-power blue tapered amplifier laser diodes and laser arrays *(Invited Paper)*

Piotr Perlin, Szymon Stanczyk, Institute of High Pressure Physics (Poland); Irina Makarowa, TopGaN Ltd. (Poland); Dario Schiavon, Institute of High Pressure Physics (Poland)

High optical power, visible and UV laser-based light sources are of great importance for many applications like e.g. color display, laser processing and curing, 3D printing, second harmonic generation etc. Generally, we can divide these sources into two categories: flood illumination sources like standard laser diode arrays to be applied in Digital Light Processing (DLP) projectors, laser processing and laser curing and high-beam quality sources needed for lithography, second harmonic generation, 3D printing, volume data storage.

The development of high-power laser diode arrays, though quite analogue to the case of their arsenide counterparts, is quite challenging because of a rather high operating current, sizable contact resistance which lead to difficult thermal managing of these devices. However, in spite of these difficulties the optical power of the order of 10 W can be achieved with good perspective for 20 W single chip light sources.

For high beam quality, high power sources the different strategy must be applied. We show that the use of tapered amplifiers provides a unique possibility of having Gaussian beam and Watt range optical power. However, nitride tapered amplifiers are challenging in its construction mostly because of the pronounced self-heating present in these devices. We will also discuss the question of the optical loss minimization, an issue important in tapered waveguide and the question of thermal beam lensing characteristic for these structures.

10123-11, Session 3

Pulse train stability of passively mode-locked semiconductor lasers *(Invited Paper)*

Oleg Nikiforov, Technische Univ. Darmstadt (Germany); Lina Jaurigue, Technische Univ. Berlin (Germany); Lukas Drzewietzki, Technische Univ. Darmstadt (Germany); Kathy Lüdge, Technische Univ. Berlin (Germany); Stefan Breuer, Technische Univ. Darmstadt (Germany)

Passively mode-locked semiconductor lasers have evolved as versatile compact photonic sources delivering ultra-short optical pulses with multi-gigahertz pulse repetition rates. The emitted optical pulse train can be affected by timing jitter, which has a non-stationary origin and is dependent on pulse width, pulse energy and repetition rate, and by amplitude fluctuations. Here, we review recent progress that contributes to the applicability of passively mode-locked semiconductor lasers by improving their timing and amplitude stability. Experimental concepts include passive electrical stabilization, and extended optical feedback configurations. The overall aim is to reduce both amplitude and timing instabilities thus accessing the increased potential of mode-locked lasers towards nonlinear imaging and time-critical applications.

10123-12, Session 3

1030-nm diode-laser-based light source delivering pulses with nanojoule energies and picosecond duration adjustable by mode-locking or pulse-gating operation

Andreas Klehr, Ferdinand-Braun-Institut (Germany); Armin Liero, Leibniz Institut für Höchstfrequenztechnik (Germany); Hans Wenzel, Frank Bugge, Olaf Brox, Jörg Fricke, Peter Ressel, Alexander Sahm, Andrea Knigge, Wolfgang Heinrich, Ferdinand-Braun-Institut (Germany); Günther Tränkle, Leibniz Institut für Höchstfrequenztechnik (Germany)

There is an increasing demand for laser systems emitting femtosecond and picosecond infrared light pulses with high pulse energies and kHz-MHz repetition rates for applications in material processing, fluorescence spectroscopy, metrology and LIDAR.

We present a new 1030-nm picosecond light source where a multi-section DBR laser acting as master oscillator (MO) is integrated with a tapered device consisting of several ridge-waveguide sections operated as an ultrafast optical gate and a flared section acting as power amplifier (PA). MO and PA are mounted together with high-frequency electronics on a 5x4-cm micro bench.

The light source can be switched between pulse gating and passive mode locking operation. For pulse gating all sections of the MO (except of the DBR section) are forward biased and driven by a constant current. By injecting electrical pulses into the RW section of the PA the CW beam emitted by the MO is converted into a train of optical pulses with adjustable widths between 250 and 1000 ps, peak powers of 20 W and spectral linewidths in the MHz range. Shorter pulses with widths between 4 and 15 ps and peak powers up to 50 W but larger spectral widths of about 300 pm are generated by mode locking where one section of the MO is reverse biased, acting as a saturable absorber. The repetition rate of 4.2 GHz of the

pulse train emitted by the MO can be reduced to values between 1 kHz and 100 MHz by utilizing the RW section of the PA as pulse picker.

10123-13, Session 3

High-performances of very long (13.5mm) tapered laser emitting at 975nm

Michel Krakowski, Patrick Resneau, Michel Garcia, Eric Vinet, Yannick Robert, Michel Lecomte, Olivier Parillaud, Bruno P. Gérard, III-V Lab. (France); Dmitri L. Boiko, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

The technology of Mode-Locked Semi-Conductor Lasers is a promising candidate considered by ESA for optical metrology systems for various space applications in the context of high-precision optical metrology, in particular for High Accuracy Absolute Long Distance Measurement. The following very challenging target performance requirements should be met: pulse duration<1ps, pulse energy > 200pJ, high spatial beam quality (M2<2.5). For pulse repetition frequency of 3GHz and pulse energy of 200pJ, the average optical power should be 600mW. We intend also to get compactness, integration of gain and absorber on the same chip, high wall plug efficiency and possibility to operate in hybrid mode-locking regime. Therefore, we have decided to address these targets by the design and fabrication of a very long (13.5mm) monolithic multiple-sections edge-emitting mode-locked tapered laser. From the rear side to the front side the laser comprises absorber sections, an intermediate and a tapered sections. On a two section Ridge test structure, 2mm long, we have obtained a uniform optical spectrum consisting of around twenty equidistantly separated modes indicating mode locking. Multi-sections tapered lasers show good inter-electrode isolation (resistances higher than 20kOhms. We have measured L(I) characteristics at different biases in CW operation at 20°C. First results show threshold current of 1.3A, optical power of 500mW at 2.5A on the tapered gain section (intermediate and absorbing sections biased at transparency and at -1V, respectively). At higher negative biases we have observed kinks corresponding to rich dynamics.

We shall present a comparative study on the electrode geometry impact on laser performances.

10123-14, Session 3

Mode-locked lasers in indium phosphide photonic-integrated circuits *(Invited Paper)*

Erwin A. Bente, Sylwester Latkowski, Valentina Moskalenko, Monica Llorens Revul, Technische Univ. Eindhoven (Netherlands); Saeed Tahvili, Technische Universiteit Eindhoven (Netherlands); Kevin A. Williams, Technische Univ. Eindhoven (Netherlands)

In this paper we present an overview of recent results and insights we obtained on modelocked laser systems that are realized on indium-phosphide technology with active-passive integration. Using available photonic integration platform technology in, the performance of integrated planar waveguide mode locked lasers can be much enhanced in comparison to all-active laser designs. Using standardized building blocks one can realize extended cavity mode locked oscillators at telecom wavelengths with increased performance and control. In this technology we have demonstrated a coherent frequency comb of over 40 nm wide at the -20dB level. By including long passive waveguides we have demonstrated repetition rates down to 2.5 GHz. By including DBR mirrors we have realized tunable short pulse lasers. Using an intra-cavity phase modulator we have recently realized a drift stabilization of the frequency comb offset, locking the comb to a single frequency laser. The possibilities of the integration technology are exploited further by combining two short pulse lasers and a single mode lasers on a single chip to form a dual frequency comb system.

Such a system has been fabricated and we hope to present first results. The performance of the integrated lasers also gives us an improvement of the understanding of details in the operation of the basic building blocks. It shows that carrier dynamics in passive sections of the laser cavity can play a role and that all electrical and optical aspects of a component need to be taken into account.

10123-15, Session 3

Monolithic/heterogeneous integration of III-V lasers on Si *(Invited Paper)*

Zhechao Wang, Univ. Gent (Belgium) and IMEC (Belgium); Bin Tian, Univ. Gent (Belgium); Marianna Pantouvaki, Clement Merkling, Joris Van Campenhout, IMEC (Belgium); Geert Morthier, Gunther Roelkens, Dries Van Thourhout, Univ. Gent (Belgium)

In the paper, we elaborate our recent work on monolithic (by epitaxial growth) and heterogeneous (by adhesive bonding) integration techniques that may pave the path to the final solutions of IIIV lasers on silicon in different scenarios. In the case of on-chip optical interconnects, a large number of IIIV lasers with high integration density are highly demanded. By using a buffer-less selective growth technique, we are able to grow submicron-sized InP waveguides directly on silicon. All the dislocations are confined at the interface between Si and InP, which leads to the successful demonstration of a distributed feedback (DFB) laser array with good uniformity. Thanks to the minimized buffer layer thickness (20 nm) and the standard top-down laser process flow, it is possible to demonstrate very high integration density of IIIV lasers on silicon. Recently, by growing InGaAs/InP heterostructures on the virtual lattice-matched InP-on-Si template, we are able to achieve room-temperature lasing at communication wavelength range.

On the other hand, the relatively mature bonding based heterogeneous integration technology has been well developed over the last decade, and the integration of various laser configurations on silicon lead to more system level demonstrations. Here, we present our recent work on IIIV-on-Si mode-locked lasers. Thanks to the extremely low silicon waveguide loss, we are able to achieve record-low repetition rate of 1GHz, with an extremely low RF linewidth (sub-kHz). Such devices are promising for applications such as spectroscopy, microwave photonics etc.

10123-16, Session 4

Advances in hybrid silicon III-V quantum-dot laser *(Invited Paper)*

Yasuhiko Arakawa, The Univ. of Tokyo (Japan); Takahiro Nakamura, Photonics Electronics Technology Research Association (Japan); Bongyong Jang, The Univ. of Tokyo (Japan); Kastuaki Tanabe, Kyoto Univ. (Japan); Misturu Sugawara, QD Laser, Inc. (Japan)

High temperature stability and high feedback-noise tolerance of the quantum dot lasers are advantageous features for application to silicon photonics. A silicon optical interposer with the bandwidth-density of 15Tbps/cm2 at 125 C was demonstrated using flip-chip bonding method. Moreover, we report the first demonstration of a hybrid silicon quantum dot (QD) laser, evanescently coupled to a silicon waveguide. InAs/GaAs QD laser structures with thin AlGaAs lower cladding layers were transferred, by means of direct wafer bonding, onto silicon waveguides defining cavities with adiabatic taper structures and distributed Bragg reflectors (DBRs). The laser operates at temperatures up to 115 °C under pulsed current conditions, with a characteristic temperature T0 of 303 K near room temperature. Furthermore, by reducing the width of GaAs/AlGaAs mesa down to 8 ?m, continuous-wave operation is realized at 25 °C.

10123-17, Session 4

Quantum cascade lasers on silicon *(Invited Paper)*

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Silicon integration of mid-infrared (MIR) photonic devices promises to enable low-cost, compact sensing and detection capabilities that are compatible with existing silicon photonic and silicon electronic technologies. Heterogeneous integration by bonding III-V wafers to silicon waveguides has previously been used to build diode lasers integrated with silicon waveguides for wavelengths from 1310 to 2010 nm. To extend this spectral range, the versatility and performance of Quantum Cascade Lasers (QCLs) at wavelengths throughout the mid-infrared range (3000-16000 nm) makes them a desirable light source for MIR silicon photonic integrated circuits.

Here we demonstrate the successful heterogeneous integration of QCLs with silicon waveguides. Tapers in the III-V mesa transfer an optical mode from the hybrid III-V/Si active region into passive silicon waveguides, and feedback is provided by reflections from both the III-V tapers and the polished passive silicon facets. We also show results of the heterogeneous integration of distributed feedback (DFB) QCLs on silicon. DFB lasers are appealing for many high-sensitivity chemical spectroscopic sensing applications in need of a single frequency, narrow-linewidth MIR source. These heterogeneously integrated Fabry-Pérot and DFB lasers could be employed as part of a MIR photonic integrated circuit. Multiple die bondings can enable the integration of multiple QCLs for different wavelengths throughout the MIR on one silicon chip.

10123-18, Session 4

InAs quantum-dot micro-disk lasers grown on (001) Si emitting at communication wavelengths *(Invited Paper)*

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To support an energy-efficient optical interconnect technology enabled by silicon photonics, development of low-energy-consumption active devices and the corresponding integration technology is needed. Most communication wavelength lasers with excellent device performance have been grown on III-V substrates and bonded to silicon. For integration, there are considerable advantages in a technology that allow the formation of such lasers from III-V-on-Si compliant substrates. Quantum dot (QD) active layers grown on lattice-matched substrates have already shown their capability for lasers with low-threshold densities and temperature-independent operation. Furthermore, the reduced sensitivity of QDs to defects and their unique capability of filtering dislocations make them an ideal candidate for the active layers of hetero-integrated III-V on Si optical sources. In this talk, we report the growth of multi-stack QDs on compliant substrates by MOCVD. Fabrication and laser characteristics of whispering-gallery-mode (WGM) micro-disk lasers using the grown epitaxial structures will also be discussed. Initial demonstration was achieved using simple a colloidal lithography process in combination with dry and wet-etching. The micro-disk lasers were one to four microns in diameter. With smooth sidewalls and sufficient undercut by wet etching of the pedestal, the air-cladded MDs can exhibit thresholds below 100 ?W. These energy-efficient MD lasers are excellent candidates for on-chip integration with silicon photonics.

10123-19, Session 4

Electrically driven QD ridge-lasers on silicon substrates

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We have previously demonstrated low threshold current, broad-area InAs/GaAs quantum dot (QD) lasers grown directly on Si, which are competitive with those grown on native substrates. We now concentrate on developing ridge-lasers, with the intention of progressing towards photonic integrated structures. We report on the single-mode lasers and investigate the performance and reliability of deep-etched InAs/GaAs QD ridge-lasers grown directly on Si substrates, emitting at 1.3µm. Deep-etched laser waveguides were formed by dry-etching to a depth of approximately 3.5µm and samples were lapped then cleaved into lengths of 2, 3 and 4mm. We characterised laser degradation in continuous-wave operation for the different cavity lengths and assessed the mechanisms which compromise performance. Over an initial run-in time of 600 hours, the shortest (2mm) laser suffers the highest degradation, with an increase in threshold current of 55% and a significant reduction in slope efficiency. The degradation reduces with increasing cavity length and for the 4mm laser the threshold current has increased by only 10% with only slight reduction in slope efficiency. In terms of electrical characteristics, there is negligible change with ageing. Single mode lasers, which are the first to be demonstrated by direct growth on Si, were formed by dry-etching 2.3µm wide mesas to within 100nm of the QD active region. Near-field measurements show a singular lasing mode as current is increased above threshold with a FWHM of ≈ 2.1µm. Room-temperature threshold current for a 1.8mm-long laser was 65mA with a slope efficiency of 0.3W/A and measured output power beyond 40mW.

10123-20, Session 5

InP-on-SOI electrically injected nanolaser diodes *(Invited Paper)*

Guillaume Crosnier, Lab. de Photonique et de Nanostructures (France) and STMicroelectronics (France); Dorian Sanchez, Paul Monnier, Isabelle Sagnes, Grégoire Beaudoin, Sophie Bouchoule, Rama Raj, Lab. de Photonique et de Nanostructures (France); Fabrice Raineri, Lab. de Photonique et de Nanostructures (France) and Univ. Paris 7-Denis Diderot (France)

The development of energy-efficient ultra-compact nanolaser diodes integrated in a Silicon photonic platform is of paramount importance for the deployment of optical interconnects for intra-chip communications.

In this work, we present our results on InP-based electrically injected photonic crystal (PhC) nanolaser integrated on a SOI waveguide circuitry. The lasers emit at room temperature in a continuous wave regime at 1560nm and exhibit thresholds of 0.1mA at 1V. We measure more than 100µW of light coupled into the SOI waveguides giving a wall-plug efficiency greater than 10%.

The principle of the lasers relies on the use of a 1D PhC nanocavity made of InP-based materials positioned on top of a SOI waveguide to enable evanescent wave coupling. More in details, the laser cavity is a 650nm-wide rib waveguide drilled with a single row of equally sized holes (radius~100nm). The distance between the holes is varied to obtain Q-factors larger than 106 for a structure fully encapsulated in silica with material volume of the order of the cubic wavelength. Vertically, the InP heterostructure is a 450nm thick NIP junction embedding 5 strained InGaAsP quantum wells emitting at 1.53µm.

By smartly positioning the metallic contacts, this configuration enables the efficient electrical injection of electron-holes pairs within the cavity without inducing optical losses which led us to demonstrate the laser emission coupled ta a Si waveguide.

10123-21, Session 5

Long-term mutual phase-locking of picosecond pulse pairs generated by a GaAs-AlGaAs core-shell nanowire laser

Benedikt Mayer, Gregor Koblmueller, Armin Regler, Sabrina Sterzl, Tom Stettner, Michael Kaniber, Walter Schottky Institut (Germany); Benjamin Lingnau, Kathy Lüdge, Technische Univ. Berlin (Germany); Jonathan J. Finley, Walter Schottky Institut (Germany)

Wavelength scale coherent optical sources are vital for a wide range of applications in nanophotonics ranging from metrology and sensing to nonlinear frequency generation and optical switching. In these respects, semiconductor nanowires (NWs) are of particular interest since they represent the ultimate limit of downscaling for photonic lasers with dielectric resonators. By virtue of their unique one-dimensional geometry NW-lasers combine ultra-high modal gain, support low-loss guided modes and facilitate low threshold lasing tuneable across the UV, visible and near infra-red spectral regions. Recently, optically pumped NW lasers have been demonstrated at room temperature and they can now be site-selectively integrated onto silicon substrates. While the fundamental carrier relaxation and gain dynamics of NW-lasers have been explored, the coherent dynamics have hitherto received comparatively little attention. In this contribution, we demonstrate that GaAs-AlGaAs core-shell nanowire lasers grown on silicon are capable of emitting pairs of phase-locked picosecond laser pulses when subject to incoherent pulsed optical excitation. By probing the two-pulse interference that emerges within the homogeneously broadened laser emission, we show that pulse pairs remain mutually coherent over timescales extending beyond ~30ps, much longer than the emitted laser pulse duration (~3 ps). Simulations performed by solving the optical Bloch equations produce good quantitative agreement with experiments, revealing how the phase information is stored in the gain medium close to transparency.

10123-22, Session 5

Lateral emission highly polarized single-mode nanobelt laser

Pengfei Xu, Shikai Liu, Ming Li, Zheng Zhou, Zhaohui Ren, Qing Yang, Zhejiang Univ. (China)

Nanoscale lasers are the key component in the integrated photonics chips and have attracted much interests. Nanoblets and nanowires lasers, as one of the candidates for the nanoscale lasers, have been developed for one more decades. Many kinds of nanowire lasers with different functionalities, such as wavelength tunable, single mode, polarized emission and so on, have been demonstrated. However, the reported single mode nanowire lasers are mostly realized through microfabrication process, careful manipulation and complicated structures. Here, we present a new type of lateral emission single mode nanobelt lasers with high polarization ratio which are fabricated by the one step traditional VLS (Vapor Liquid Solid) growth. Different from the traditional nanobelt lasers which are based on the FP cavity formed in the longitudinal direction, the emission of this novel nanoblet laser is lateral which is contribute to the special wire-like structures grown on the nanobelt. It shows band edge emission and the wavelength is centered at 712.6 nm with linewidth about 0.18 nm. The threshold reach as low as 15 uJ/cm2 benefit from the unique morphology which provides enhanced confinement factor for optical modes. Meanwhile the laser emission is highly polarized with polarization ration as high as 0.91. This lateral emission single mode nanobelt laser with high polarization ratio, low threshold and simple fabrication technique offers an economic and effective choice to the future optical applications.

10123-23, Session 5

Novel hybrid laser modes in composite VCSEL-DFB microcavities

Andreas Mischok, Tim Wagner, Markas Sudzius, Robert Brückner, Hartmut Fröb, Vadim G. Lyssenko, Karl Leo, TU Dresden (Germany)

Two of the most successful microcresonator concepts are the vertical cavity surface emitting laser (VCSEL), where light is confined between distributed Bragg reflectors (DBRs), and the distributed feedback (DFB) laser, where a periodic grating provides positive optical feedback to selected modes in an active waveguide (WG) layer. Our work concerns the combination of both into a composite device, facilitating coherent interaction between both regimes and giving rise to novel laser modes in the system. In a first realization, a full VCSEL stack with an organic active layer is evaporated on top of a diffraction grating with a large period (approximately 1 micron), leading to diffraction of waveguided modes into the surface emission of the device. Here, the coherent interaction between VCSEL and WG modes, as observed in an anticrossing of the dispersion lines, facilitates novel hybrid lasing modes with macroscopic in-plane coherence [1].

In further studies, we decrease the grating period of such devices to realise DFB conditions in a second-order Bragg grating which strongly couples photons via first-order light diffraction to the VCSEL. This efficient coupling can be compared to more classical cascade-coupled cavities and is successfully described by a coupled oscillator model [2]. When both resonators are non-degenerate, they are able to function as independent structures without substantial diffraction losses. The realization of such novel devices provides a promising platform for photonic circuits based on organic microlasers.

[1] A. Mischok et al., Adv. Opt. Mater., early online, DOI: 10.1002/adom.201600282, (2016)

[2] T. Wagner et al., Appl. Phys. Lett., accepted, in production, (2016)

10123-24, Session 6

High-power 1.9-3.3-um type-I quantum-well cascade diode lasers *(Invited Paper)*

Leon Shterengas, Takashi Hosoda, Meng Wang, Tao Feng, Gela Kipshidze, Gregory Belenky, Stony Brook Univ. (United States)

Cascade pumping of type-I quantum well gain sections improved both efficiency and continuous wave (CW) output power of GaSb-based diode lasers. Coated devices with ~100 µm wide aperture and 3-mm-long cavity demonstrated CW output power of 1.96 W near 2 µm, 980 mW near 3 µm, 500 mW near 3.18 µm and 360 mW near 3.25 µm at room temperature. Narrow ridge cascade diode lasers devices generating nearly diffraction limited output beams demonstrated ~200 mW near 2 and ~100 mW near 3 ?m. The results of the optimization of the laser heterostructure and ridge geometry designs targeting high power single mode operation will be presented.

10123-25, Session 6

High internal differential efficiency mid-infrared quantum cascade lasers *(Invited Paper)*

Dan Botez, Jeremy D. Kirch, Chun-Chieh Chang, Colin Boyle, Honghyuk Kim, Kevin M. Oresick, Chris Sigler, Luke J Mawst, Univ. of Wisconsin-Madison (United States); Minhyeok Jo, Jae Cheol Shin, Yeungnam Univ. (Korea, Republic of); Gun-Kim Doo, Photonics Technology Institute (Korea, Republic of); Don F. Lindberg III, Thomas L. Earles, Intraband, LLC (United States)

Implementing the step-taper active-region design to 8-9 ?m-emitting quantum cascade lasers (QCLs) has resulted in both high T0 and T1 values: 220 K and 665 K, and low lower-level lifetimes: 0.12 ps. In turn, internal-differential-efficiency values of ~ 86 % were obtained for both 8.4 ?m- and 8.8 ?m-emitting QCLs. Achieving both carrier-leakage suppression and miniband-like carrier extraction in mid-infrared (IR) QCLs leads to internal-differential-efficiency values close to fundamental limits of ~ 90 %. Therefore, the currently employed fundamental wallplug-efficiency limits over the mid-IR wavelength range (i.e., Appl. Phys. Lett. 90, 253512 (2007)) can be increased by ~ 30 %..

10123-26, Session 6

5.6um quantum cascade lasers with 28% wallplug efficiency

Matthew M. Suttinger, Univ. of Central Florida (United States); Rowel Go, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Ankesh Todi, Pedro N. Figueiredo, Arkadiy A. Lyakh, Univ. of Central Florida (United States)

The absolute record in quantum cascade laser efficiency of 27% has been reported for a shallow-well active region design comprising five different materials [1]. However, many epi-growth reactors are configured to grow structures with only two alternating active region barrier and quantum well layers. The data presented in this work demonstrate that it is possible to achieve a laser performance comparable to that of the shallow-well design for active region designs based only on two materials. This significantly simplifies commercialization of high performance quantum cascade lasers.

40-stage ?=5.6 μm quantum cascade lasers with a new design based on Al0.78In0.22As/In0.69Ga0.31As active region composition have been developed. Maximum room temperature wall plug efficiency of 28% was measured under pulsed operational conditions with 200ns-long pulses and 10kHz repetition rate for 3mm by 9μm uncoated devices. The high laser performance is attributed to increased laser dynamic range (Jmax/Jth>5) and increased injection efficiency (~75%). The latter was measure using 1/L approach for chips with variable cavity length. The presented laser design is compatible with high duty cycle and continuous wave modes of operation.

References:

[1] Y. Bai, N. Bandyopadhyay, S. Tsao, S. Slivken, and M. Razeghi, Applied Physics Letters 98, 181103 (2011)

10123-27, Session 7

Novel coupled-cavity sensing mechanism for on-chip detection of microparticles

Sara-Jayne Gillgrass, Robert Thomas, Peter M. Smowton, Cardiff Univ. (United Kingdom)

Coupled-cavity lasers have attracted wide attention in the past, in particular for telecommunication applications where their wavelength tunability and ability for side mode suppression are desirable. The inherent sensitivity of these devices to changes in the optical coupling has also led to their proposed use in optical sensing systems. Small changes to the refractive index of the coupler section can lead to shifts in the resonance frequency of the laser.

Here we present an alternative approach to coupled-cavity sensing that exploits changes to the imaginary part of the refractive index of the coupler. An optical loss, introduced to the cavity by the passage of micro-particles, influences the optical loss of the lasing mode and changes the threshold gain requirement of the laser. The sub-linear nature of the gain-current density characteristics of the quantum confined gain medium amplifies this effect, producing an even larger perturbation in output power. We demonstrate this sensing mechanism using a monolithic coupled-cavity particle detector with on-chip capillary fill microfluidics and an in-line photo-detector section for photo-voltage transduction. Both laser and detector are pulsed allowing for a time-resolved measurement to be taken.

10123-28, Session 7

785-nm dual-wavelength Y-branch DBR-RW diode laser with electrically adjustable wavelength distance between 0 nm and 2 nm

Bernd Sumpf, Julia Kabitzke, Jörg Fricke, Peter Ressel, André Müller, Martin Maiwald, Günther Tränkle, Ferdinand-Braun-Institut (Germany)

Shifted excitation Raman difference spectroscopy is a powerful tool to separate the weak Raman lines from disturbing background light like fluorescence, day and artificial light. When exciting the sample alternatingly with two slightly shifted wavelengths, the Raman lines follow the change whereas the background remains unchanged. Subtracting the signal and using reconstruction algorithms background free Raman spectra can be obtained. Here, optimized signal-to-noise ratios can be reached, when the spectral distance between the two wavelengths is the width of the Raman lines under study.

In this work, monolithic dual wavelength Y-branch DBR ridge waveguide diode lasers with resistor heaters over the DBR gratings will be presented. The devices have a total length of 3 mm and a RW stripe width of 2.2 μm. The wavelengths are defined by 500 μm long 10th order gratings with a designed spectral distance of 0.62 nm. Using the resistor heaters, this distance can be adjusted.

The monolithic devices reach output powers up to 180 mW. Over the full range they operate single mode. The emission width is smaller than 13 pm (FWHM). At an output power of 50 mW the conversion efficiency amounts 0.22, which only slightly decreases down to 0.18 at maximal power. At an output power of 100 mW and with heater currents smaller than 600 mA, the spectral distance can be tuned from 0 nm up to 2 nm. The spectra remain single mode.

SERDS experiments with different spectral distances were performed with ethanol and red wine as fluorescent media.

10123-29, Session 7

Very narrow spectral width 1.65um tunable high-power laser

Igor V. Kudryashov, Evgenii Y. Kotelnikov, Princeton Lightwave, Inc. (United States)

Growing interest in precise measurements of methane concentration is stimulating efforts to develop tunable high power laser source in the spectral region of 1.65 μm.

We developed fiber coupled, narrow line, tunable, high reliable, compact and robust laser source based on injection locking approach.

We present the results of our experimental and theoretical studies of locking injection of a power semiconductor laser diode by weak external source with very narrow spectral width. As a master oscillator we used a fiber coupled low power (<15mW) DFB laser. A fiber coupled high power (>450mW) Fabry-Perot (FP) ridge waveguide (RWG) InGaAsP/InP 1.65um laser diode was utilized as a slave laser. We demonstrated that spectrum of the locked laser mimicked the master oscillator spectral properties without significant degradation. Benefits and limitations of external seeding of semiconductor lasers were theoretically and experimental investigated including the S/N ratio in spectral domain.

We investigated a variety of factors, which impact on injection locking stability and spectral range: master/ slave power ratio, detuning a master spectral position.

The developed laser source exhibit low spectral width <10MHz at >400mW of CW output power in a single mode fiber. Tuning range >1nm was demonstrated.

10123-30, Session 7

Monolithic dual-wavelength diode lasers with sub-MHz narrowband emission at 785 nm

Martin Maiwald, Ferdinand-Braun-Institut (Germany); Christoph Raab, Wilhelm G. Kaenders, TOPTICA Photonics AG (Germany); Bernd Sumpf, Günther Tränkle, Ferdinand-Braun-Institut (Germany)

Spectrally stabilized diode lasers are requested for several low- and high-resolution spectroscopic applications. For absorption spectroscopy of gases at normal pressure and Raman spectroscopy of solids and liquids, dual-wavelength diode lasers with an emission width below 10 pm were recently published. To address sub-Doppler spectroscopy and other highly sensitive detection techniques a smaller emission width is requested.

In this paper, a monolithic dual-wavelength diode laser at 785 nm will be analyzed with respects to the emission line-width. The wavelengths are realized by two implemented deeply-etched 10th-order 500 μm long distributed Bragg reflector (DBR) gratings with different periods using i-line wafer stepper lithography. The laser light is guided via 2.2 μm wide ridge waveguides and a Y-branch section is implemented to realize a common output section. The diode laser has a footprint of 3 x 0.5 mm.

At 20°C the device has an optical power of 150 mW at an injection current of 300 mA for each emission wavelength. Here, a total power consumption of 0.7 W is observed. A spectral distance of 0.6 nm is measured over the whole power range. The spectral linewidth is measured with a delayed self-heterodyne setup. Up to 40 mW optical power the emission shows a linewidth below 500 kHz and up to 80 mW below 1 MHz. Moreover, stability tests and noise properties of both emission lines where investigated.

The results demonstrate that besides the already demonstrated suitability of these devices for Raman spectroscopy, the dual-wavelength devices have also the potential for sub-Doppler spectroscopy.

10123-31, Session 7

3D micro-lenses for free space intra-chip coupling in photonic-integrated circuits

Robert Thomas, Gwilym I. Williams, Sam Ladak, Peter M. Smowton, Cardiff Univ. (United Kingdom)

The integration of multiple optical elements on a common substrate to create photonic integrated circuits (PIC) has been successfully applied in: fibre-optic communications, photonic computing and optical sensing. The push towards III-Vs on silicon promises a new generation of integrated devices that combine the advantages of both integrated electronics and optics in a single substrate. III-V edge emitting laser diodes offer high efficiency and low threshold currents making them ideal candidates for the optically active elements of the next generation of PICs. Nevertheless, the highly divergent and asymmetric beam shapes intrinsic to these devices limits the efficiency with which optical elements can be free space coupled intra-chip; a capability particularly desirable for optical sensing applications e.g. [1]. Furthermore, the monolithic nature of the integrated approach prohibits the use of macroscopic lenses to improve coupling. However, with the advent of 3D direct laser writing, three dimensional lenses can now be manufactured on a microscopic-scale [2], making the use of micro-lens technology for enhanced free space coupling of integrated optical elements feasible.

Here we demonstrate the first use of 3D micro-lenses to improve the coupling efficiency of monolithically integrated lasers. Fabricated from IP-dip photoresist using a Nanoscribe GmbH 3D lithography tool, the lenses are embedded directly onto a structured GaInP/AlGaInP substrate containing arrays of ridge lasers free space coupled to one another via a 200 ?m air gap. We compare the coupling efficiency of these lasers with and without micro-lenses through photo-voltage and beam profile measurements and discuss optimisation of lens design.

10123-32, Session 8

High-power and self-detected dual quantum cascade laser frequency combs *(Invited Paper)*

Jérôme Faist, ETH Zürich (Switzerland)

By exploiting the broad gain curve of quantum cascade laser active regions and by a suitable dispersion engineering, optical frequency combs that combine high power (up to a watt) and broad coverage (100cm-1) can be achieved. We also demonstrate that these devices can be used as their own detectors, simplifying radically a potential sensing system.

10123-33, Session 8

Self-detection QCL-based dual-comb spectroscopy setup

Pierre Jouy, Gustavo F. Villares, Johanna Wolf, Filippos Kapsalidis, Mattias Beck, Jérôme Faist, ETH Zürich (Switzerland)

In the recent years, we demonstrated Quantum Cascade Laser (QCL) based dual comb spectroscopy in the mid-IR by combining two comb beams on a fast detector. It was shown as well that, by using a RF bias-tee between the QCL current driver and the QCL, the RF spectrum containing the comb repetition frequency can be recorded.

In this work, we demonstrate a new integrated approach for dual comb spectroscopy based on a self-detection scheme. We inject the optical beam of a QCL comb directly into another QCL which produces as well his comb. By properly choosing slightly different frequency repetition rates for both combs, we can obtain the multi-heterodyne beat spectrum through the RF port of a bias-tee placed between the current driver and the injected QCL. In this manner, this QCL acts both as a source and a detector, allowing to simplify considerably the dual comb spectroscopy setup by removing the fast detector. An optical isolator as well as a variable attenuator were placed after the injecting QCL to prevent the formation of an external cavity and gain stability. The QCL combs have a frequency centered around 7.6 ?m. The difference of frequency repetition rate is of about 5.3 MHz and approximately 150 lines are visible on the multi-heterodyne beat signal. This corresponds to a coverage of 50 cm-1 in the optical spectra with a resolution of 0.33 cm-1. Those preliminary results are extremely encouraging and spectroscopy measurements will be performed using this self-detection dual comb setup.

10123-34, Session 8

Broadly tunable quantum cascade laser arrays for handheld spectroscopy

Christian J. Pfluegl, Romain Blanchard, Biao Li, Laurent Diehl, Masud Azimi, Mark Witinski, Peili Chen, Daryoosh Vakhshoori, Pendar Technologies (United States)

This presentation discusses recent advancements of monolithic broadly tunable Quantum Cascade Laser (QCL) sources with particular focus on chip design, beam combining and packaging to miniaturize the sources to make them suitable for handheld and portable applications.

This presentation will also cover the spectroscopic concepts and results enabled by those mid-infrared sources. In optical systems, such as standoff detectors and in situ gas analyzers, this increases analyte sensitivity and selectivity by broadening spectral source coverage and by allowing for extremely fast all-electronic wavelength tuning with no moving parts.

10123-35, Session 8

Mid-infrared on-chip sensing technologies *(Invited Paper)*

Boris Mizaikoff, Univ. Ulm (Germany)

Mid-infrared (MIR; 3-20 µm) sensor technology is increasingly applied in environmental analysis, process monitoring and biodiagnostics due to the inherent molecular specificity enabling the discrimination of molecular components at ppm-ppb concentration levels. Recently emerging strategies taking advantage of innovative waveguide technologies including substrate-integrated hollow waveguides for detecting vapor phase media, and thin-film planar waveguides for analyzing liquid or solid state samples in combination with highly efficient light sources including quantum cascade and interband cascade lasers facilitate the development of compact and robust MIR on-chip sensing platforms for label-free chem/bio sensing and diagnostics.

10123-36, Session 9

Terahertz quantum-cascade metasurface VECSELs *(Invited Paper)*

Benjamin S. Williams, Luyao Xu, Christopher A. Curwen, Univ. of California, Los Angeles (United States); John L. Reno, Sandia National Labs. (United States); Tatsuo Itoh, Univ. of California, Los Angeles (United States)

Terahertz quantum-cascade vertical external cavity surface emitting laser (VECSELs) are made possible through the development of amplifying reflectarray metasurfaces. The metasurface is made up of sub-wavelength arrays of antenna coupled sub-cavities loaded with quantum-cascade active material. The QC-VECSEL approach allows scaling of laser power while maintaining a high quality, near diffraction limited beam - something which has been a long standing challenge for THz quantum-cascade lasers with sub-wavelength metallic waveguides. The latest results of cavity and metasurface engineering are presented, including the demonstration of a focusing reflectarray metasurface that enables a “flat-optics” hemispherical VECSEL cavity, with improved geometric stability and a Gaussian profile beam with beam quality parameter of M2=1.3.

10123-37, Session 9

Terahertz plasmonic lasers with ultra-narrow beams and large tunability *(Invited Paper)*

Yuan Jin, Lehigh Univ. (United States); Chongzhao Wu, Columbia Univ. (United States); John L. Reno, Sandia National Labs. (United States); Sushil Kumar, Lehigh Univ. (United States)

A distributed-feedback method is developed for metal-clad plasmonic-lasers with sub-wavelength dimensions, which establishes a surface-plasmon-polariton mode in the surrounding medium of laser’s cavity with a large wavefront and allows such plasmonic-lasers to radiate in narrow beams. Experimental demonstration is done for terahertz quantum-cascade lasers (QCLs) that show beam-divergence as small as 4-degrees, the narrowest reported to-date. We also report 57GHz reversible, continuous, and mode-hop-free tuning of such QCLs operating at 78K based on post-process deposition/etching of a dielectric on an already mounted QCL chip. This is the largest tuning range achieved for terahertz QCLs when operating much above liquid-Helium temperature.

10123-38, Session 9

Broadband monolithic extractors for terahertz frequency combs

Markus Rösch, Ileana-Cristina Benea-Chelmus, ETH Zurich (Switzerland); Giacomo Scalari, Christopher B. Bonzon, Martin J. Süess, Mattias Beck, Jérôme Faist, ETH Zürich (Switzerland)

Recent work has been showing the possibility of generating frequency combs at terahertz frequencies using terahertz quantum cascade lasers. The main efforts so far were on getting the laser to work in a stable comb operation over an as broad as possible spectral bandwidth. Another issue is the scattered farfield of such combs due to their subwavelength facets of the used metal-metal waveguide. In contrast to single mode lasers the monolithic approaches of distributed feedback lasers or photonic crystals cannot be used. We present here a monolithic broadband extractor compatible with frequency comb operation based on the concept of an end-fire antenna. The antenna can be fabricated using standard fabrication techniques. It has been designed to support a bandwidth of up to 600 GHz at a central frequency of 2.5 THz. The fabricated devices show single lobed farfields with only minor asymmetries, increased output power along an increased dynamical range of frequency comb operation. A side-absorber schematics using a thin film of Nickel has been used to suppress any higher-order lateral modes in the laser. The reported frequency combs with monolithic extractors are ideal candidates for spectroscopic applications at terahertz frequencies using a self-detected dual-comb spectroscopy setup due to the increased dynamical range along with the improved farfield leading to more output power of the frequency combs.

10123-39, Session 9

The 4.7-THz quantum-cascade laser local oscillator on SOFIA *(Invited Paper)*

Heinz-Wilhelm Hübers, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany) and Humboldt-Univ. zu Berlin (Germany); Heiko Richter, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Martin Wienold, Humboldt-Univ. zu Berlin (Germany) and Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Lutz Schrottke, Klaus Biermann, Holger T. Grahn, Paul-Drude-Institut für Festkörperelektronik (Germany)

High-resolution terahertz (THz) heterodyne spectroscopy is an important technique in astronomy. So far frequencies above 2.5 THz could not be accessed by this technique because of the lack of a suitable local oscillator. A novel local oscillator based on a THz quantum-cascade laser allows for the observation of the fine-structure line of neutral atomic oxygen at 4.7448 THz. The local oscillator has been implemented in the GREAT (German REceiver for Astronomy at Terahertz frequencies) spectrometer on SOFIA, the Stratospheric Observatory for Infrared Astronomy. The design and the performance of the local oscillator will be presented.

10123-40, Session 10

Narrow-linewidth ultra-broadband terahertz sources based on difference-frequency generation in mid-infrared quantum cascade lasers *(Invited Paper)*

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We discuss novel approaches to improve the bandwidth and efficiency of terahertz (THz) sources based on difference-frequency generation (DFG) in mid-infrared quantum cascade lasers (QCLs), including active region designs aimed to optimize both doubly-resonant nonlinearity and the optical rectification nonlinearity, epi-transfer of the laser material to silicon substrates, and devices configurations aimed to improve the extraction efficiency of THz radiation. We will also discuss spectral characteristics of THz emission in these THz DFG-QCLs and show that they are suitable to operate as local oscillators.

10123-41, Session 10

Terahertz difference frequency generation in quantum cascade lasers on silicon

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We demonstrate that an application of a III-V-on-Silicon hybrid concept to terahertz (THz) Cherenkov difference frequency generation (DFG) quantum cascade laser (QCL) sources (THz DFG-QCLs) can dramatically improve the mid-infrared-to-THz conversion efficiency if a high-resistivity Si substrate is used. Favorable optical properties of a high-resistivity Si include refractive index (nSi~3.42) well-matched to the group index of mid-infrared pumps (ng~3.37), low refractive index dispersion, and virtually no absorption loss in 1-6 THz range. As a result, unlike native InP substrates of THz DFG-QCLs, THz high-resistivity silicon can provide long THz extraction length, high THz transmission, beam-steering-free tunable operation, and facet-polishing-free THz out-coupling. Completely processed THz DFG-QCLs grown on a 660-μm-thick native InP substrate are transfer-printed onto a 1-mm-thick high-resistive Si substrate using a 100-nm-thick SU-8 as an adhesive layer. Room temperature device performance of the reference InP and hybrid Si THz DFG-QCLs of the same ridge width (22 μm) and cavity length (4.2 mm) have been experimentally compared. The target THz frequency of 3.5 THz is selected for both devices using the dual-period first order surface gratings to select the mid-infrared pump wavelength of 994 cm-1 and 1110 cm-1. At the maximum bias current, the reference InP and hybrid Si devices produced THz power of 50 μW and 270 μW, respectively. The mid-infrared-to-THz conversion efficiency corresponds to 60 μW/W2 and 480 μW/W2, respectively, resulting in 5 times higher THz power and 8 times higher conversion efficiency from the hybrid devices.

10123-42, Session 10

Superfluorescent laser sources based on single-wall carbon nanotube films

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High-quality thin films of highly aligned semiconducting single-wall carbon nanotubes have been recently demonstrated. They have excellent absorption and photoluminescence properties; however, fast nonradiative recombination of carriers prevents their use as a gain medium in lasers. Here we predict that such films can operate as efficient sources of ultrashort radiation pulses under the conditions of superfluorescence, i.e. cooperative interband recombination of injected electrons and holes. Superfluorescence develops much faster than nonradiative recombination and leads to high-intensity, coherent pulses of near/mid-infrared radiation.

10123-43, Session 10

Quantum structures for recombination control in the light-emitter transistor

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Recombination of carriers in the direct-bandgap base of a transistor-injected quantum cascade laser (TI-QCL) is shown to be controllable through the field applied across the quantum cascade region located in the transistor's base-collector junction. The influence of the electric field on the quantum states in the cascade region's superlattice allows free flow of electrons out of the transistor base only for field values near the design field that provides optimal QCL gain. Quantum modulation of base recombination in the light-emitting transistor is therefore observed. In a GaAs-based light-emitting transistor, a periodic superlattice is grown between the p-type base and the n-type collector. Under different base-collector biasing conditions the distribution of quantum states, and as a consequence transition probabilities through the wells and barriers forming the cascade region, leads to strong field-dependent mobility for electrons in transit through the base-collector junction. The radiative base recombination, which is influenced by minority carrier transition lifetime, can be modulated through the quantum states alignment in the superlattice. A GaAs-based transistor-injected quantum cascade laser with AlGaAs/GaAs superlattice is designed and fabricated. Radiative base recombination is measured under both common-emitter and common-base configuration. In both configurations the optical output from the base is proportional to the emitter injection. When the quantum states in the superlattice are aligned the optical output in the base is reduced as electrons encounter less impedance entering the collector; when the quantum states are misaligned electrons have longer lifetime in the base and the radiative base recombination process is enhanced.

10123-60, Session PWed

Fabrication and characterization of photonic-crystal surface-emitting lasers with triangular double-hole lattice points

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Recently, W-class photonic-crystal surface-emitting lasers (PCSELs) with both a single spectrum and narrow spot beam pattern have been reported. These highly coherent PCSEL properties cause a highly bright laser light that will be useful for various applications. To improve the PCSEL output power, it is important to enlarge the emitting area to reduce the heat generation effect. However, multi-mode oscillation will occur in a broad emitting area because the difference in the threshold gain between the fundamental and higher modes becomes narrower as the emitting area is broadened. In this work, we fabricated PCSELs with double-hole lattice points that decrease the optical confinement to prevent multi-mode oscillation.

The fabricated device, consisting of an AlGaAs/InGaAs material system designed to be oscillated at a wavelength of 940nm, has an emitting area of 300 ? 300 ?m2. In a square lattice photonic crystal whose lattice period equals the lasing wavelength embedded in PCSELs, the distance between the centers of the double hole was set to one quarter of the lasing wavelength to decrease in-plane coupling caused by interference. We confirmed that this device was oscillated at the ? point of band edge A in the photonic band structure. The peak power is more than 5 W under pulse operation at 10 A. The device has a narrow beam divergence of less than 1º and single lobe spectrum in spite of the broad emitting area, so these double-hole lattice points are an effective structure to improve the PCSEL output power.

10123-61, Session PWed

Quantum-cascade vertical-cavity surface-emitting laser

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This paper proposes a design for the first quantum-cascade vertical-cavity surface-emitting laser (QC VCSEL). Presently QC lasers can be fabricated in horizontal cavity geometry since stimulated emission from quantum cascades is possible if electrical component of the electromagnetic wave is perpendicular to the QC surface. That field component is absent in vertical cavity, which makes fundamentally impossible fabrication of QC VCSELs in their conventional design.

In our novel design, the top VCSEL mirror is a monolithic high-refractive-index contrast grating (MHCG), which serves as both an optical coupler and as the region in which the vertical component of the electrical field is induced, enabling stimulating emission from the quantum cascades.

Using a three-dimensional, fully vectorial optical model, the properties of different MHCGs as possible QC VCSEL mirrors are analysed. The distribution of the optical field and the threshold gains of VCSELs with QCs embedded in MHCGs are also simulated.

Our analysis shows that the vertical component of the electric field of the electromagnetic wave can be induced in the region of the MHCG, where it stimulates emission in the quantum cascades embedded in the MHCG stripes and enables to reach the threshold for vertical laser emission.

The possibility of fabricating QC VCSELs opens perspectives for merging the advantages of VCSELs with those of QC lasers. QC VCSELs are expected to emit a good quality beam with minimal divergence, exhibit low threshold current, enable integration into two-dimensional arrays (as with VCSELs) and emit in the micrometer spectral range (as do QC lasers).

10123-44, Session 11

High brightness diode lasers controlled by volume Bragg gratings *(Invited Paper)*

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Volume Bragg gratings (VBGs) recorded in photo-thermo-refractive (PTR) glass are holographic optical elements that are effective spectral and angular filters withstanding high power laser radiation. Reflecting VBGs are narrow-band spectral filters while transmitting VBGs are narrow-band angular filters. The use of these optical elements in external resonators of semiconductor lasers enables extremely resonant feedback that provides dramatic spectral and angular narrowing of laser diodes radiation without significant power and efficiency penalty. Spectral narrowing of laser diodes by reflecting VBGs demonstrated in wide spectral region from near UV to 3 μm. Commercially available VBGs have spectral width ranged from few nanometers to few tens of picometers. Efficient spectral locking was demonstrated for edge emitters (single diodes, bars and stacks), vertical cavity surface emitting lasers (VCSELs), grating coupled surface emitting lasers (GCSELs), and interband cascade lasers (ICLs). The use of multiplexed VBGs provides multiwavelength emission from a single emitter. Spectrally locked semiconductor lasers demonstrated CW power from milliwatts to a kilowatt. Angular narrowing by transmitting VBGs enables single transverse mode emission from wide aperture diode lasers having resonators with great Fresnel numbers. This feature provides close to diffraction limit divergence along a slow axis of wide stripe edge emitters. Radiation exchange between lasers by means of spatially profiled or multiplexed VBGs enables coherent combining of diode lasers. Sequence of VBGs or multiplexed VBGs enable spectral combining of spectrally narrowed diode lasers or laser modules. Thus the use of VBGs for diode lasers beam control provides dramatic increase of brightness.

10123-45, Session 11

High power vertical stacked diode laser development using macro-channel water cooling and hard solder bonding technology

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Water-cooled diode laser stacks have been adopted in many applications. "Micro-Channel Coolers (MCCs)" is a common packaging architecture. However, their reliability are subjected to conductivity of cooling water (must <5 ?S cm-1) and operational condition (working under on-off current-cycling is problematic).

A marco-channel vertical stacked package has been developed utilizing "Indium-free" packaging technology. A marco-channel cooler is employed to reduce the risk of water erosion and electro-chemical induced corrosion. Laser bar is P-side mounted on a CTE-matched cooper-tungsten (CuW) thin chip on which AuSn hard solder has been deposited. Hard solder is also introduced to soldering cooper-tungsten to MaCC cooler. Gold wire bonding process is introduced.

Sample devices are characterized. Maximum power device can safely operating at is 100W/bar (30ms pulse duration, 10Hz frequency, 30% duty cycle), while maximum slop efficiency is up to 1.5W/A. Maximum power of 400W/bar has also reached (250?s, 400Hz, 10% duty cycle), while corresponding spectrum values of FWHM and FW 90% are 2.9nm and 3.4nm. Thermal impedance factor is recorded in range of 0.46-0.55 K/Watt.

A lifetime test is conducted to evaluate reliability. MaCC vertical stacks along with indium MCC counterparts are operating under condition of 100A current and 30% duty cycle in micro-second scale. All samples are supplied with tap water with conductivity of 130-150?S cm-1, device exhibits power degradation greater than 5% will be regard as failure. First few failures are founded on indium MCC samples at 2500 hours?while none of MaCC sample fail before 5000 hr.

In conclusion, novel marco-channel vertical stacked packages have been developed utilizing "Indium-free" packaging technology. The performances have been characterized, a lifetime test against MCC counterparts have conducted.

10123-46, Session 11

1030-nm DBR-tapered diode lasers with up to 16 W of optical output power

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Non-linear frequency conversion of near-infrared diode lasers currently remains the method of choice towards high-power, diffraction-limited emission in the green spectral range. Corresponding light sources are of special interest for applications such as biomedical imaging with Titanium:Sapphire lasers. Using compact and efficient diode lasers brings the advantage of addressing specific wavelengths with respect to the application and may help to increase the widespread adoption of diode laser based blue-green laser systems.

In this work we present our recent results for 1030 nm distributed Bragg reflector (DBR) tapered diode lasers with optimized designs of ridge-waveguides and grating structures. The lasers are based on an asymmetric super large optical cavity containing an InGaAs triple quantum well. The selected vertical layer structure results in a low vertical far field angle of 15° full width at half maximum, enabling easy beam shaping. A deep implantation through the active zone next to the ridge-waveguide is applied in order to suppress propagation of lateral side modes. Intrinsic wavelength stabilization by 7th order DBR gratings, realized by electron-beam lithography, reduces the spectral emission widths down to about 20 pm over the whole power range. At a heatsink temperature of 15°C the developed lasers provide up to 16 W optical output power. About 9 W are contained in the diffraction-limited central lobe. The maximum obtained electro-optical efficiencies are 57%. Based on these parameters the lasers are well suited for efficient non-linear frequency conversion.

10123-47, Session 11

Direct measurement of the 2D gain profile in a tapered semiconductor laser

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Single mode tapered semiconductor lasers producing watt-class output powers often suffer from beam quality degradation as drive current increases. The dominant degradation mechanism is believed to be poor gain clamping in the periphery of the optical mode; as the injection current is increased, excess gain in this region eventually leads to parasitic lasing in the amplifier section of the device. However, this effect has not previously been directly observed and other effects such as thermal lensing and gain guiding also likely contribute. Nevertheless, it has been previously shown that by engineering the overlap of the gain profile with the nonuniform optical intensity distribution, performance can be significantly improved. In this work, we report on the direct observation and mapping of the 2D gain profile in a tapered semiconductor laser. InGaAsP-based tapered diode lasers are fabricated with windowed openings on the back (substrate) side of the chip. The devices are soldered junction down for continuous wave operation. An optical microscope is used to observe and map the 2D spontaneous emission profile, and hence gain and carrier density, of the device under operation. The results are compared to a theoretical model to better understand the physical limitations of beam quality degradation in tapered diode lasers.

10123-48, Session 11

On-chip unstable resonator cavity 2-micron diode lasers

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Type-I quantum well (QW) lasers at 2-3 μm spectral band have important applications such as spectroscopy, remote sensing, and pumping of solid state lasers. In many cases, higher brightness is desirable, however filamentation in broad area devices severely degrades the beam quality and brightness. To suppress filamentation, we have fabricated devices with an unstable resonator (UR) geometry, where one cylindrical mirror is formed on the back facet by Focused Ion Beam (FIB) milling. We measure far-field properties of the emitted beam, and find that the beam quality of UR devices is substantially improved when compared to standard Fabry-Pérot (FP) devices. For example, a 0.1mmX3mm UR cavity diode laser with a back facet mirror radius of 3mm (magnification of ~3) exhibits a virtual source waist of 27 μm, whereas the effective waist size in the FP cavity device is ~100 μm. Despite the slightly lower slope efficiency, a near 4-fold increase in brightness is observed at 10 times threshold. This suggests a successful suppression of filaments in an on-chip UR cavity, the first such demonstration in a ~2μm GaSb-based diode laser.

10123-49, Session 11

Power degradation and reliability study of high-power laser bars at QCW operation

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The solid state laser relies on the laser diode pumping array. Typically for high peak power QCW operation, the energy output per pulse and long term reliability is critical. With the improved bonding technique, specially Indium-free bonded laser bars, most of the failure was caused by failure within laser diode itself (wearout failure), which are induced from dark line defect (DLD), bulk failure, point defect generation and etc. Measuring the reliability of LD at QCW condition will take a rather long time. Alternatively, an accelerating model could be a quicker way to estimate the LD life time at QCW operation. In this report, laser bars were mounted on micro channel cooling heat sink and operated at QCW condition with different current density and junction temperature (Tj) recorded. The Tj control is achieved by changing pulse width and frequency. The major concern here is the wearout failure and the power degradation. Reliability models of QCW and its corresponding failures are studied. In conclusion, QCW accelerated life-time model is discussed, with a few variable parameters. The model is compared with CW model to found their relationship

10123-50, Session 12

Far-infrared InAs-based quantum cascade lasers *(Invited Paper)*

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The development of InAs-based QCLs was initially inspired by a giant conduction band offset between InAs and AlSb, essential to fabricate short wavelength QCLs. The InAs/AlSb material family made possible fabrication of the first QCLs emitting below 3.5 µm. The shortest QCL emission wavelength of 2.6 µm has been obtained in the InAs-based lasers. In the far-infrared devices it is possible to fully exploit another advantage of this material family, the small electron effective mass in InAs, providing a high QCL gain because this benefit is higher when the lasing transition levels are close to the bottom of the conduction band and the effect of nonparabolicity is weak. Employing a double-metal surface plasmon waveguide we demonstrated InAs-based QCLs emitting at 16-21 µm and operating up to room temperature in pulsed mode. Further performance improvement and, notably, a decrease in the RT threshold current density below 1 kA/cm2 has been obtained in the devices with a dielectric InAs-based waveguide and a design optimized to reduce the QCL transparency current. This progress allowed us to achieve the cw regime at room temperature in lasers emitting at 15 µm, now the longest cw RT wavelength for any semiconductor laser. Due to the small optical phonon energy compared with GaAs- and InP-based materials the InAs/AlSb QCLs are supposed to be able to enter farther into the reststrahlen band, providing emitters for the region near 30 µm not yet accessible for semiconductor lasers. The higher intersubband gain can also be exploited in THz QCLs.

10123-51, Session 12

Resonant tunneling diodes based on ZnO for quantum cascade structures

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The terahertz (THz) spectral range (lambda ~ 30µm – 300µm) is also known as the "THz-gap" because of the lack of compact semiconductor devices. Various real-world applications would strongly benefit from such sources like trace-gas spectroscopy or security-screening. A crucial step is the operation of THz-emitting lasers at room temperature. But this seems out of reach with current devices, of which GaAs-based quantum cascade lasers (QCLs) seem to be the most promising ones. They are limited by the parasitic, non-optical LO-phonon transitions (36meV in GaAs), being on the same order as the thermal energy at room temperature (kT = 26meV). This can be solved by using larger LO-phonon materials like ZnO (E_LO = 72meV). But to master the fabrication of ZnO-based QC structures, a high quality epitaxial growth is crucial followed by a well-controlled fabrication process including ZnO/ZnMgO etching.

We use devices grown on m-plane ZnO-substrate by molecular beam epitaxy. They are patterned by reactive ion etching in a CH4-based chemistry (CH4:H2:Ar/30:3:3 sccm) into 50µm to 150µm square mesas. Resonant tunneling diode structures are investigated in this geometry and are presented including different barrier- and well-configurations. We extract contact resistances of 8e-5 Omega cm^2 for un-annealed Ti/Au contacts and an electron mobility of above 130cm^2/Vs, both in good agreement with literature. Proving that resonant electron tunneling can be achieved in ZnO is one of the crucial building blocks of a QCL.

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10123-52, Session 12

Single-photon superradiance and collective Lamb shift in a semiconductor quantum device *(Invited Paper)*

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Superradiance is one of the many fascinating phenomena predicted by quantum electrodynamics that have first been experimentally demonstrated in atomic systems and more recently in condensed matter systems like quantum dots, superconducting q-bits, cyclotron transitions and plasma oscillations in quantum wells (QWs).

It occurs when a dense collection of N identical two-level emitters are phased via the exchange of photons, giving rise to enhanced light-matter interaction, hence to a faster emission rate. Of great interest is the regime where the ensemble interacts with one photon only and therefore all of the atoms, but one, are in the ground state. In this case the quantum superposition of all possible configurations produces a symmetric state that decays radiatively with a rate N times larger than that of the individual oscillators. This phenomenon, called single photon superradiance, results from the exchange of real photons among the N emitters. Yet, to single photon superradiance is also associated another collective effect that renormalizes the emission frequency, known as cooperative Lamb shift.

In this work, we show that single photon superradiance and cooperative Lamb shift can be engineered in a semiconductor device by coupling spatially separated plasma resonances arising from the collective motion of confined electrons in QWs. These resonances hold a giant dipole along the growth direction z and have no mutual Coulomb coupling. They thus behave as a collection of macro-atoms on different positions along the z axis. Our device is therefore a test bench to simulate the low excitation regime of quantum electrodynamics.

10123-53, Session 12

Laser-driven parametric generation of coherent THz radiation in graphene and topological insulators

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Massless Dirac electrons in graphene and on the surface of 3D topological insulators such as Bi2Se3 demonstrate strong nonlinear optical response and support tightly confined surface plasmon modes. Although both systems constitute an isotropic medium for low-energy in-plane electron excitations, their second-order nonlinear susceptibility becomes non-zero when its spatial dispersion is taken into account. In this case the anisotropy is induced by in-plane wave vectors of obliquely incident or in-plane propagating electromagnetic waves. In this work we develop a rigorous quantum theory of the second-order nonlinear response and apply it to the parametric amplification of mid-infrared and Thz radiation. We show that a strong near-infrared or mid-infrared laser beam obliquely incident on graphene can experience a parametric instability with respect to decay into lower-frequency (idler) photons and THz surface plasmons. The parametric gain leads to efficient generation of THz plasmons. Furthermore, the parametric decay process gives rise to quantum entanglement of idler photon and surface plasmon states. This enables diagnostics and control of surface plasmons by detecting idler photons. A similar parametric process can be implemented in topological insulator thin films.

10123-54, Session 13

Long-term reliability study and failure analysis of quantum cascade lasers

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Here we present lifetime test results of 4 groups of quantum cascade lasers (QCL) under various aging conditions including an accelerated life test. The total accumulated life time exceeds 1.5 million device•hours, which is the largest QCL reliability study ever reported. The longest single device aging time was 46.5 thousand hours (without failure) in the room temperature test. Four failures were found in a group of 19 devices subjected to the accelerated life test with a heat-sink temperature of 60 °C and a continuous-wave current of 1 A. Visual inspection of the laser facets of failed devices revealed an astonishing phenomenon, which has never been reported before, which manifested as a dark belt of an unknown substance appearing on facets. Although initially assumed to be contamination from the environment, failure analysis revealed that the dark substance is a thermally induced oxide of InP in the buried heterostructure semi-insulating layer. When the oxidized material starts to cover the core and blocks the light emission, it begins to cause the failure of QCLs in the accelerated test. An activation energy of 1.2 eV is derived from the dependence of the failure rate on laser core temperature. With the activation energy, the mean time to failure of the quantum cascade lasers operating at a current density of 5 kA/cm2 and heat-sink temperature of 25°C is expected to be 809 thousand hours.

10123-55, Session 13

The effects of interface roughness on quantum cascade lasers

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Quantum cascade (QC) lasers achieve population inversion by selecting quantum wells (QW) thicknesses so that the inherent scattering mechanisms ensure a higher population of electrons in the upper laser state compared to the lower laser state. Previously, longitudinal optical (LO) phonons have been considered the fastest, most significant scattering process in QC lasers. Recently, it has been shown that interface roughness (IFR) can have substantial effects in determining the effective lifetimes within QW systems [1]. Simulations have shown that IFR scattering lifetimes can be the dominant scattering process for selected QW configurations [2].

Here we have designed and fabricated three QC structures, which differ in the positioning of a strategically placed monolayer barrier to selectively affect the IFR scattering lifetimes of the energy levels in the QC structures. Initial current-voltage characteristics suggest a shorter carrier transit time through the QC structure due to increased interface roughness interactions. We also observed an expected narrowing of the EL spectra based on these same interactions. Using these results, we have also designed a QC laser using IFR scattering as the determining process for maintaining population inversion. By using IFR scattering, we were able to design an energy separation between the lower laser level and subsequent injector levels much greater than the LO phonon energy without compromising fast carrier depopulation from the lower laser level. This in effect opens doors for completely new intersubband design techniques. This work is supported in part by MIRTHE (NSF-ERC).

10123-56, Session 13

Multi-heterodyne spectroscopy using Fabry-Perot interband cascade lasers for trace gas detection

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Interband-cascade lasers (ICLs) have proven to be efficient semiconductor sources of coherent mid-infrared (mid-IR) radiation. Single mode distributed-feedback (DFB) ICLs are excellent spectroscopic sources for targeting important molecular species in the mid-IR fingerprint region with high-resolution, but are limited to a narrow spectral tuning range. Recent developments in another mid-IR semiconductor laser technology, quantum cascade lasers (QCLs), have demonstrated significant progress towards broadband high-resolution spectroscopic sensing applications with multi-mode Fabry-Perot (FP) QCLs using multi-heterodyne spectroscopy (MHS). FP-QCL based MHS has demonstrated spectroscopic chemical detection with a minimum fractional absorption down to ~1e-4/Hz1/2, a bandwidth of tens of wavenumbers, an acquisition time on the order of 10 μs/spectrum, and a spectral resolution in the single MHz range. Here we characterize the performance of FP-ICLs and demonstrate similar trace gas detection capabilities using FP-ICL based MHS. Free-running FP-ICLs exhibit frequency jitter and drift, which decrease spectroscopic reliability and broaden the RF beatnotes. In this work, we demonstrate analog real-time feedback control used to reduce the offset frequency drift by controlling the injection current of the lasers. A new post-processing algorithm based on computational adaptive sampling techniques is used to suppress the offset and repetition frequency jitter. With this setup we enable room temperature FP-ICL MHS for broadband high-resolution spectroscopic measurements that achieve an RF beatnote frequency stability of 50kHz over an acquisition time of 10s and an absorption detection limit comparable to FP-QCL MHS.

10123-57, Session 13

Al0.45Ga0.55As/GaAs–based single-mode distributed-feedback quantum-cascade lasers with surface gratings

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Distributed-feedback mid-infrared (?-10?m) quantum-cascade lasers based on Al0.45Ga0.55As/GaAs structure [1] were elaborated for single–mode operation. First order, 1?m-deep, Bragg surface gratings, with period width ? in the range 1.40-1.60μm, were etched exactly in the topmost n+ GaAs:Si layer playing the role of the top cladding of the laser's plasmon-enhanced waveguide. For setting the pattern of gratings down, the standard DUV photolithography was performed in MJB-3 Süss-MicroTech system. Etching of GaAs layer was performed with BCl3/Ar mixtures in ICP RIE Plasmalab System 100 Oxford Instruments, with the generator powers PICP=180W and PRIE=100W. The Si3N4 was used as a mask during formation of gratings. The ~7μm-deep ridge waveguides, with widths W=15μm, 25μm, 35μm, were fabricated by wet etching in H3PO4:H2O2:H2O solution. Extended alloyed contacts (5nm Ni/100nm AuGe/35nm Ni/250nm Au) were isolated with 300nm–thick Si3N4. Then the wafer polishing and the alloyed ohmic contact (225nm AuGe/75nm Ni/300nm Au) on the back side were done. The lasers were cleaved with resonator length 1.5mm, and remained uncoated.

At 77K the wavenumber difference ~12cm^-1 was observed for different lasers with ridge width W=25μm, which were fabricated, however, from the same epitaxial structure. The emission wavelength could be tuned with temperature at a rate 1nm/K, in the range 77-120K. The full width at half maximum of the emitted spectra was below 0.4cm^-1.

[1] Kosiel K, Kubacka-Traczyk J, Sankowska I, Szerling A, Gutowski P, Bugajski M 2012 Multi-step interrupted-growth MBE technology for GaAs/

AlGaAs (?9.4 ?m) room temperature operating quantum-cascade lasers
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10123-58, Session 13

Heat dissipation schemes in QCLs monitored by CCD thermoreflectance

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In this paper we present the development of the instrumentation for accurate evaluation of the thermal characteristics of quantum cascade lasers based on CCD thermoreflectance (CCD TR). This method allows rapid thermal characterization of QCLs, as the registration of high-resolution map of the whole device facet lasts only several seconds. The capabilities of the CCD TR are used to study temperature dissipation schemes in different designs of QCLs.

We report on the investigation of thermal performance of QCLs developed at the Institute of Electron Technology, with an emphasis on the influence of different material system, processing technology and device designs. We investigate and compare AlInAs/InGaAs/InP QCLs (lattice matched and strain compensated) of different architectures, i.e., double trench and buried heterostructure (BH) in terms of thermal management.

Experimental results are in very good agreement with numerical predictions of heat dissipation in various device constructions. Numerical model is based on FEM model solved by commercial software package. The model assumes anisotropic thermal conductivity in the AR layers as well as the temperature dependence of thermal conductivities of all materials in the project.

We have observed experimentally improvement of thermal properties of devices based on InP materials, especially for buried heterostructure type. The use of buried heterostructure enhanced the lateral heat dissipation from the active region of QCLs. The BH structure and epilayer-down bonding help dissipate the heat generated from active core of the QCL.

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10124-1, Session 1

Does nanowire LED become a reality? *(Invited Paper)*

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High-brightness, packaged LED market is still increasing thanks to significant cost-reduction. However, breakthroughs are needed to pursue the trends. Up to now, the driving forces were first an increase of the performances in terms of lm/W (which is now clamped close to the maximum theoretical value) and secondly an increase of the substrate sizes in order to decrease the lumen cost. But conventional LEDs (either on sapphire or on silicon) suffer from large lattice and thermal coefficient mismatches between the active area and the substrates that prevents LED industry to continue to benefit from cost reduction thanks to the scaling effect.

Wide-bandgap gallium nitride (GaN) nanowires (NWs) are considered to be able to change the paradigm and are foreseen as attractive building blocks for high efficiency and low cost solid-state lighting applications. In this paper, we will present an overview of this innovative technology.

We will review the different device designs used and we will associate them with their corresponding market segments. A focus will be performed on the different electrical, optical and structural performances of the nanowires obtained.

Finally, full devices performances will be presented.

10124-2, Session 1

Top-down fabricated III-nitride nanowire photonics *(Invited Paper)*

George T. Wang, Sandia National Labs. (United States)

III-nitride nanowires have attracted increasing interest for next-generation LEDs and as potential ultracompact and low-power nanoscale lasers in the UV-visible wavelengths. In order to maximize the potential of nanowire-based photonics, a greater understanding and control over their properties, including mode control, polarization control, wavelength tuning, and beam shaping, is necessary. Here, we discuss the fabrication of III-nitride based nanowire LEDs and lasers using a two-step top-down approach, and present advances in understanding and controlling their optical properties. The nanowires were fabricated by a two-step process composed of a lithographic dry etch followed by a highly crystallographic anisotropic wet chemical etch of the nanowire sidewalls. This powerful technique allows for high quality nanowires and other nanostructures with straight and smooth nonpolar m-plane sidewalls and with controllable height, pitch and diameter. Precisely engineered axial nanowire heterostructures can be formed from planar heterostructures, while radial nanowire heterostructures can be formed via regrowth on the etched nanowires.

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.

10124-3, Session 1

Recent developments of 3D GaN architectures for solid-state lighting *(Invited Paper)*

Andreas Waag, Jana Hartmann, Hao Zhou, Sönke Fündling, Johannes Ledig, Frederik Steib, Hutomo S. Wasisto, Hergo-Heinrich Wehmann, Technische Univ. Braunschweig (Germany); Tilman Schimpke, Martin Mandl, Adrian Avramescu, Ion Stoll, Martin Strassburg, Hans-Jürgen Lugauer, OSRAM Opto Semiconductors GmbH (Germany)

GaN nanorods and related high aspect ratio 3D GaN nanostructures recently attracted a lot of attention since they are expected to be an exciting new route towards extending the freedom for device design in GaN technology. Such structures offer large surfaces, defect free high quality material, as well as non-polar surface orientations, including the possibility to use very large area foreign substrates without implementing large area strain. All of these aspects are difficult or impossible to achieve when planar substrate approaches are used.

Meanwhile, such 3D high aspect ratio GaN based nanostructures can reproducibly be fabricated with high aspect ratios and good homogeneity, and more and more device and application aspects are under investigation.

Besides nano- and microrods, fin geometries offer all of the advantages of high aspect ratio nanostructures. High aspect ratio GaN structures with smooth non-polar {11-20} a-plane sidewalls were grown by selective area growth in continuous mode MOCVD. These fins reached heights of more than 50 ?m using growth rates of of up to 203 ?m/h. Depending on orientation, width and pitch of the line openings as well as on the growth parameters, different structural quality evolved. Both the MOCVD growth as well as properties of fin and nano/microrod structures will be compared. Besides nanorods, fin geometries could be an interesting alternative for 3D devices based on nitrides, like solid state lighting and vertical electronics.

10124-4, Session 2

III-nitride quantum dots for ultra-efficient LEDs *(Invited Paper)*

Jonathan J. Wierer Jr., Xiongliang Wei, Nelson Tansu, Lehigh Univ. (United States)

There has been impressive progress in III-nitride LEDs for solid-state lighting; however, they can only achieve high efficiencies at low current densities (<10A/cm2) because of parasitic Auger recombination. Methods to reduce carrier density at a particular operating current in these quantum-well-based LEDs have only provided marginal efficiency improvements. As an alternative, we present simulations using InGaN quantum dots (QDs) as active layers. QD-based LEDs can achieve higher efficiencies at higher current densities because of higher spontaneous emission rates and reduced Auger recombination. Simulations of violet-emitting QD-LEDs show ultra-high efficiencies (>80 %) up to current densities of 500 A/cm2. The challenge to realizing these improvements is to find methods to synthesize QDs to achieve the required sizes, inhomogeneous broadening, and densities. If constructed properly, these QD-LEDs could offer a method to overcome Auger recombination and achieve breakthrough efficiencies.

10124-5, Session 2

A high-performance full-color microdisplay based on quantum-dot aerosol jet technology *(Invited Paper)*

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Currently, the light utilization efficiency (LUE) of LCD display is still lower than 2.8 %. Most passive components such as color filters can absorb a large portion of emitted photons from LED backlight. Thus the display needs to be operated at more than ten times of the required power in order to meet the expected output luminescence.The RGB quantum dots (QDs) can be a great alternative candidate to realize full color display and solve the low light utilization efficiency problem in LCD system. The QDs possess unique properties such as high quantum yield, size-dependent emission wavelength, and narrow emission FWHM. This study reports a full-color LED based display by combining UV micro-LED arrays with 282 pixels per inch (PPI) in full color by RGB QDs via aerosol jet printing technology.

10124-6, Session 2

Improved color metrics in solid-state lighting via utilization of on-chip quantum dots

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Quantum Dots (QDs) have long been implicated for uses in solid-state lighting. In particular, their narrow, tunable emission characteristics make them desirable for use as a downconverter for both LED lighting and display applications. While there are currently QD used in display applications, to date, on-chip applications of QDs have been very challenging. This is due to the intense flux and heat that QDs in an on-chip application must be able to withstand. However, here, we demonstrate on-chip QD downconverters as a direct replacement for red phosphor in LED lighting. In particular, we show long-term reliability data showing the practicality of using QD materials in standard HTOL and WHTOL stress conditions. Additionally, we model improvements of using QDs as a phosphor replacement as a function of wavelength, emission width, and quantum yield to demonstrate at least a 10% improvement in LER over industry standard red phosphors for warm white lighting applications; an improvement that grows as a function of CRI and R9. Approximately 107 QD lighting sample spectra have been generated from a model based on real devices to show the relative impact of QDs at various CCT/CRI/R9 values. As a lower limit to the QD emission linewidth, single QD room-temperature emission spectra are used as inputs to the model. Furthermore comparisons to ensemble emission characteristics show that some single particle linewidths can be as large as or larger than the ensemble values, signifying the emission profile is not simply a function of size heterogeneity.

10124-7, Session 2

Hybrid white inorganic/organic LEDs using organic colour converters

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In this work, we present an alternative approach for producing white light-emitting diodes (LEDs) that utilises the best of both worlds by combining a highly-efficient inorganic blue LED with the versatility of individually-designed organic colour converters. Advantages of using organic colour converters include relatively straightforward synthesis with the ability to fine-tune photophysical properties by molecular design, fast response times and facile processing. Several organic converters have been synthesised and investigated for their ability to generate white light when combined with blue LEDs. Each organic converter consists of a blue absorbing component and a yellow emissive component. For deposition on the blue LED, the organic material was embedded into a transparent matrix. The first compound is based on the BODIPY unit. White light was achieved but the colour rendering capabilities were poor due to the limited emission in the green spectral range. To correct this, the emissive and absorbing units were replaced to include more green spectral components as well as to increase the overlap between the absorption band of the organic molecule and the blue LED emission. This led to an improvement in colour rendering as well as a threefold increase in blue-to-white efficacy (ratio of white luminous flux and blue radiant flux). The LEDs were also investigated for their ability to produce warm and cool white light, angular emission dependence and their lifetime. Overall, our results demonstrate the flexibility of organic colour converters to produce hybrid white LEDs with good colour conversion capabilities and great potential for solid-state lighting.

10124-8, Session 2

Broadband white-emitting amorphous yttrium-alumino-borate phosphors for high CRI w-LEDs

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In view of the recent lanthanides crisis, several allied industries, primarily phosphors, magnets, etc., are looking for new alternatives for the lanthanide elements [1]. Phosphors top this list owing to its core dependence, and gradually shifting the attention to other paramagnetic centers, such as the d-orbital active ions as in $K_2SiF_6:Mn^{4+}$ and $SrB_4O_7:Bi^{2+}$ commercial phosphors. Certain insulating materials with defects also show broadband visible luminescence that can be useful for phosphor application.

Recently, we observed that the amorphous yttrium aluminoborates (g-YAB) obtained by polymeric precursor (Pechini) synthesis exhibits intense defects luminescence under UV excitation covering whole visible spectrum [2] Figure 1a presents the luminescence spectra of g-YAB powders. Both luminescence intensity and spectral shape show strong dependence on the sintering temperature. Amongst, the 740-750 °C sintered g-YAB reveals intense white luminescence (Fig. 1b). These g-YAB powders exhibit high luminescence quantum yield (i-QY) of about 90% and the color rendering index (CRI) of about 94, suggesting their potential for high efficacy, high CRI white light phosphors for solid state lighting under UV LEDs excitation [3]. Further study on understanding of luminescence mechanism is in progress through detailed investigation of the defects centers present in g-YAB using various spectroscopic techniques.

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10124-9, Session 2

Controlling resonant energy transfer between phosphors with nanophotonic multi-layered structures for luminescent colour mixing

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In 1948, Theodor Förster first reported an optical radiationless dipole-dipole interaction between pairs of emitters – the so-called Förster Resonance Energy Transfer (FRET) – distant a few-nanometres away from each other, in which one quantum of energy is transferred from a first emitter – donor – to a second emitter – acceptor. Plenty of studies have been made regarding how to control this phenomenon, since a vast amount of applications may be achieved with this interaction, ranging from LED and photovoltaics to biology, sensing, lighting and magneto-optics.

Our study addresses, theoretically and experimentally, the possibility to control the energy transfer between two different molecules - an acceptor dye and a donor dye - by changing the environment in which these molecules are embedded in. Inserted in a multi-layered structure and excited by a well-controlled pulsed laser, these dyes experience different distributions of electromagnetic field depending on the thickness of the medium and the different materials that compose it, which in turn alters its decay lifetime and, consequently, the energy transfer between them. To this aim, the optical properties of donors and acceptors as well as a mixture of them in multi-layered structures are experimentally characterized by steady state Photoluminescence Measurements (PLM) and Time Resolved Measurements (TRM). Factors such as concentration and mixing of different phosphors are also covered. Besides one-dimensional multi-layered structures, we also study the effects of plasmonic nanostructures in such media, and their effects on the FRET rate and the consequent generation of different colours.

10124-10, Session 2

How to distinguish elastically scattered light from Stokes-shifted light for solid-state lighting

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Energy efficient generation of white light has become an important issue in recent years. Technology of white-light emitting diodes (LEDs) is one of the promising directions. The main challenges in the LED production are understanding scattering, absorption and emission from ab-initio, and obtain chromaticity independent emission directions. Physical understanding of multiple light scattering in the LED can provide us with simple tools for extracting optical parameters of this system.

We have studied the transport of light through phosphor diffuser plates that are used in commercial solid-state lighting modules (Fortimo). These polymer plates contain YAG:Ce+3 phosphor particles that both elastically scatter light and Stokes shift light in the visible wavelength range (400-700 nm). We excite the phosphor with a narrowband light source, and measure spectra of the outgoing light. The Stokes shifted light is spectrally separated from the elastically scattered light in the measured spectra. Using this technique we isolate the elastic transmission of the plates. This result allows us to extract the transport mean free path ltr over the full wavelength range by employing diffusion theory. Simultaneously, we determine the absorption mean free path labs in the wavelength range 400 to 530 nm where YAG:Ce+3 absorbs. The diffuse absorption ($\mu\_a=1/l\_abs$) spectrum is qualitative similar to the absorption coefficient of YAG:Ce+3 in powder, with the diffuse spectrum being wider than the absorption coefficient. We propose a design rule for the solid-state lighting diffuser plates.

10124-11, Session 3

Recent progress in GaN on Si LEDs *(Invited Paper)*

Colin J. Humphreys, Univ. of Cambridge (United Kingdom)

Growing GaN LEDs on large area Si substrates can substantially reduce the cost of LEDs and enable new functionality. 150 mm GaN on Si wafers can now be routinely grown completely crack free, with no melt back, wafer bow<50 micron, and threading dislocation density 10^8 cm^-2. A number of companies are now manufacturing such LEDs, including Plessey and Samsung.

The cost of Si substrates is substantially less than sapphire or SiC. However this is only a small part of the savings from growing GaN on Si. Further savings come from the automatic processing available in a Si foundry, giving increased yield, increased reproducibility, cassette to cassette wafer handling and reduced manpower. Additional savings come from Chip Scale Packaging (CSP), Wafer Scale Packaging (WSP), and Chip Scale Optics (CSO). Further savings can come from integrating LEDs with Si electronic functions in smart lighting.

The ease with which the Si substrate can be directionally etched facilitates the use of micro-LEDs in transfer printing, for the integration of GaN devices on a variety of substrates such as glass, plastic and fabrics.

Finally, we have recently been growing cubic GaN on 3C-SiC on (001) Si, on 150mm wafers. The absence of internal electric fields may help to solve the green gap problem and give more efficient green LEDs. Optimising the growth conditions gives close to 100% cubic phase and strong green emission.

10124-12, Session 3

Single-step manufacturing process for the production of graphene-V/III LED heterostructures *(Invited Paper)*

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Graphene has been speculated on as an ideal material for GaN LED transparent conductive layers [1,2]. However, many issues exist with graphene-LED integration. These include metal residue (e.g. Cu, Fe) and polymer contamination from graphene growth and transfer; optical and electrical conductivity non-uniformities over large areas; Ohmic contact issues; graphene being not as easy to deposit as other transparent conductive layer materials, such as indium-tin oxide (ITO); graphene fabrication not being compatible with LED processing and packaging; and the high cost involved of combining graphene with LED materials.

In this work, we demonstrate a method for integration of graphene as a contact layer with GaN LEDs which solves all of these issues. Our results prove no metal or polymer contamination, along with unrivalled material uniformity across an entire wafer of GaN material. The deposition process uses industry-standard equipment, and thus this technique is fully compatible with LED processing; this additionally helps to reduce manufacturing costs by removing the need for graphene transfer. Vf of the devices was recorded to be lower and a power enhancement was recorded over devices made from the same epitaxial material with ITO as the contact material.

Thus, we have for the first time shown a graphene fabrication process suitable for industrial GaN LED integration, which yields competitive results over conventional contacting technologies, with reduced overall cost.

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10124-13, Session 3

Effects of Mg pre-flow, memory, and diffusion on the growth of p-GaN with MOCVD

Charng-Gan Tu, Hao-Tsung Chen, Sheng-Hung Chen, Chen-Yao Chao, Yean-Woei Kiang, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

In MOCVD growth, two key factors for growing a p-type structure, when the modulation growth or delta-doping technique is used, include Mg memory and diffusion. With high-temperature growth (>900 degree C), doped Mg can diffuse into the under-layer. Also, due to the high-pressure growth and growth chamber coating in MOCVD, plenty Mg atoms exist in the growth chamber for a duration after Mg supply is ended. In this situation, Mg doping continues in the following designated un-doped layers. In this paper, we demonstrate the study results of Mg pre-flow, memory, and diffusion. The results show that pre-flow of Mg into the growth chamber can lead to a significantly higher Mg doping concentration in growing a p-GaN layer. In other words, a duration for Mg buildup is required for high Mg incorporation. Based on SIMS study, we find that with the pre-flow growth, a high- and a low-doping p-GaN layer are formed. The doping concentration difference between the two layers is about 10 times. The thickness of the high- (low-) doping layer is about 40 (65) nm. The growth of the high-doping layer starts 10-15 min after Mg supply starts (Mg buildup time). The diffusion length of Mg into the AlGaN layer beneath (Mg content reduced to <5 %) is about 10 nm. The memory time of Mg in the growth chamber is about 60 min, after which the Mg doping concentration is reduced to <1 %.

10124-14, Session 3

Investigation of the time-dependent failure of InGaN-based LEDs submitted to reverse-bias stress

Matteo Meneghini, Matteo Buffolo, Nicola Renso, Carlo De Santi, Nicola Trivellin, Gaudenzio Meneghesso, Enrico Zanoni, Univ. degli Studi di Padova (Italy)

Over the last years, the degradation of InGaN LEDs has been extensively investigated; most of the papers described the degradation of LEDs under forward bias. On the other hand, only few reports described the degradation of LEDs under reverse bias.

This paper demonstrates that when InGaN LEDs are submitted to a constant reverse bias, they can show a time-dependent breakdown, that leads to the catastrophic failure of the devices. By submitting green and blue LEDs to constant voltage stress in the range between -40 V and -60 V we demonstrate that: (i) under reverse bias conditions, current is focused on localized paths, whose positions can be identified by electroluminescence measurements, and that originate from the presence of extended defects; (ii) during a constant voltage stress, the reverse current of the LEDs gradually increases; (iii) for longer stress times, all devices show a time-dependent breakdown; (iv) time-to-failure has an exponential dependence on stress voltage, and is Weibull-distributed.

Based on the experimental evidence, the time-dependent failure of the devices is explained as follows: under reverse bias, the (almost intrinsic) active region is highly depleted, and subject to a high electric field, thus behaving as a leaky dielectric. Defects may be formed either due to the flow of highly-accelerated carriers through leakage paths, or to a time-dependent generation/percolation process similar to what is commonly observed in dielectrics. The catastrophic failure is reached when the defects created as a consequence of reverse-bias form a conductive path between the n-side and p-side of the junction.

10124-15, Session 3

Blue LED mass production in a close-coupled showerhead MOCVD tool

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We report the mass production of blue LEDs on dry-etched patterned sapphire substrates using the AIX R6 tool in a 31x4" configuration. The system was operated in a continuous run mode, i.e. cleaning the showerhead after a series of LED runs. Production stability was characterized by monitoring of wavelength, light output power (LOP), and electrostatic discharge (ESD) yields. We developed a dynamic multi-zone Topside Temperature Control and the TEQualizer function. The TEQualizer function is based on a 400nm pyrometry open loop wafer surface temperature control, using Inside P400 by Laytec. Combining this wafer-to-wafer and run -to-run temperature stability improvement with an optimized wafer carrier, we demonstrated an on-wafer uniformity of stdv of 1.1nm, a wafer-to-wafer uniformity of stdv 1.1nm and a run-to-run reproducibility of stdv <1nm, resulting in a total wafer area wavelength yield of >90% in a 6 nm bin. LOP stability was demonstrated within a 3% window with no visible run-to-run trend. An absolute buffer layer growth temperature window was defined through a Design of Experiment on buffer layers targeting best ESD yield - in particular looking into defect related morphology and its correlation with Inside P400 readings. We have demonstrated an ESD yield >90% in continuous run mode to be used in the mass production of InGaN based blue LEDs.

10124-16, Session 4

InGaN/GaN dot-in-nanowire monolithic LEDs and lasers on (001) silicon *(Invited Paper)*

Pallab K. Bhattacharya, Arnab Hazari, Univ. of Michigan (United States); Shafat Jahangir, University of Michigan, Ann Arbor (United States)

Low threshold visible lasers and efficient LEDs are useful for a number of applications including full color mobile projectors, optical data storage, heads-up displays in automobiles, in medicine and plastic fiber communication. Lasers emitting in the blue and green are generally realized with GaN-based InGaN/GaN quantum wells (QWs) as the gain media. However, there are materials-related issues that compromise the performance characteristics and prevent the epitaxy of quantum wells for lasers emitting at longer wavelengths. InGaN disks in GaN nanowires grown epitaxially on (001) silicon substrate have been exploited as the emission media in light emitting diodes. From structural and optical characterization we have confirmed that Volmer-Weber quantum dots are formed in the center of the InGaN disks. The emission wavelength of the dots can be varied from 530nm (green) to 1460nm (near-IR). We will describe the epitaxy, fabrication and characteristics of green and red-emitting dot-in-nanowire LEDs grown on (001) silicon and, in particular, the role of nanowire coalescence induced defects on the performance characteristics. We will also describe the static and dynamic characteristics of edge-emitting electrically injected high performance dot-in-nanowire monolithic lasers grown directly on (001) silicon. The near-IR lasers are important for silicon photonics.

10124-17, Session 4

Classical and quantum light generation using nitride-based semiconductor micro- and nanostructures *(Invited Paper)*

Yong-Hoon Cho, KAIST (Korea, Republic of)

We present classical and quantum light generation based on various types of group III-nitride micro- and nano-structures. We fabricated three-dimensional GaN-based pyramidal, annular, columnar, and tapered rod structures, on which InGaN/GaN quantum wells structures were grown by metal-organic chemical vapor deposition. We demonstrate phosphor-free white-color light emission with pyramidal and annular structures [1], unidirectional light propagation in energy-gradient, tapered core-shell rod structures [2], ultrafast single photon generation from a quantum dot formed at the apex of pyramid structures [3], and exciton-polariton formation at room-temperature in bulk GaN and GaN/InGaN core-shell rod structures [4].

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10124-18, Session 4

Highly scattering layer for efficient LED light extraction

Kyoungsik Kim, Changuk Kim, Seunghwa Baek, Yonsei Univ. (Korea, Republic of)

Light emitting diodes (LEDs) are used to very diverse fields because of their high efficiency and long life time. Especially, GaN-based LEDs has good properties such as high power and electrical stability, so it can be used for light source in many devices. However, because of large difference of refractive index between SiC substrate of LEDs and air, Fresnel reflection loss and Total internal reflection loss are occurred. For that reason, light extraction efficiency of LEDs is very low. In this study, we fabricate Alumina based scattering film and show light extraction efficiency of LEDs can be enhanced through attaching scattering film on SiC substrate. Alumina nanowires were fabricated by wet etching process of porous alumina layer. Nanowires were collapsed randomly by capillary force of water during drying process forming microscale ridges. This scattering film has extremely high transmittance and scattering value which is determined by etching time. The effective refractive index of the film lies between the refractive index of SiC and air. So attached scattering film on SiC substrate of LEDs creates gradually varying index distribution reducing Fresnel reflection loss. Microscale ridges of scattering film play as light scatterers, and incidence light scattered in all direction reducing incident angle dependence so they can reduce total internal reflection loss. Light extraction efficiency of scattering film attached LED is about 20% higher than bare LED.

10124-19, Session 4

Limits of cascading in high-efficiency mid-infrared superlattice light-emitting diodes

John P. Prineas, Aaron Muhowski, Cassandra Bogh, Sydney Provence, Russell J. Ricker, Thomas F. Boggess, The Univ. of Iowa (United States)

High-power infrared light-emitting diodes are a key device in infrared optoelectronic applications due to their ease of fabrication as large arrays, high radiance and large modulation bandwidth compared to blackbodies, and large, smooth radiance dynamic range lacking threshold [1,2]. InAs/GaSb superlattices are effective for mid-infrared emitters due to their tunability, Auger suppression, and insensitivity to Shockley-Read-Hall scattering at high carrier density [3]. Here the dependence of superlattice light emitting diodes' (SLED) efficiency and maximum output on the number of stages is presented.

SLED devices consist of InAs/GaSb superlattices separated by n-AlInAsSb/p-GaSb tunnel junctions [4] and variable numbers of stages N up to large N. All samples are grown by molecular beam epitaxy and lattice matched to GaSb substrates. Small arrays with variable size mesas from 25x25 um2 to 400x400 um2 are fabricated from wafers. Samples are cooled in a variable temperature cryostat, and light-current-voltage (LIV) curves are measured under quasi-CW conditions. External quantum efficiency and wallplug efficiency are determined from the LIV curves and compared. External quantum efficiency is found to scale with N, while wallplug efficiency is found to depend on current but not on N. Apparent temperatures approaching 3,000K over the 3-5 um band are demonstrated.

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10124-20, Session 5

Origin of Shockley-Read-Hall nonradiative recombination centers in (Al,Ga)N *(Invited Paper)*

Shigefusa F. Chichibu, Kazunobu Kojima, Tohoku Univ. (Japan); Akira Uedono, Univ. of Tsukuba (Japan)

(Invited) With respect to (Al,In,Ga)N epilayers and quantum wells, threading dislocations (TDs) have long been said to the principal limiting factor for the internal quantum efficiency of the near-band-edge (NBE) emission. However, as we have been suggesting for 12 years, point defect complexes containing cation vacancies are the true origin of predominant Shockley-Read-Hall nonradiative recombination centers (NRCs) in wide bandgap group-III nitride semiconductors. Accordingly, their concentration must be decreased both in optical devices and power-switching electronic devices. In this presentation, nonradiative lifetime of the NBE emission and the relative intensity of characteristic emission bands originating from the deep-states in various GaN crystals and Al0.6Ga0.4N epilayers of various Si-doping concentrations are compared with the concentration of cation vacancies, based on the results of steady-state and time-resolved photoluminescence and positron annihilation measurements.

Room-temperature nonradiative lifetime of the NBE emission in GaN crystals of a variety of orientations, polar directions, and polytypes, which were grown by various growth techniques, increases with the decrease in concentration or size of Ga vacancies and with the decrease in gross concentration of point defects including complexes. The results indicate that nonradiative recombination process is governed by the defects introduced with the incorporation of Ga vacancies, such as Ga-vacancy and N-vacancy complexes. The increase in the concentration of cation vacancies gives rise to the increase in the intensity ratio of the characteristic deep emission band to the NBE emission in Al0.6Ga0.4N alloys.

10124-21, Session 5

High modulation bandwidth of a light-emitting diode with surface plasmon coupling

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Besides lighting, LEDs can be used for indoor data transmission. Therefore, a large modulation bandwidth becomes an important target in the development of visible LED. In this regard, enhancing the radiative recombination rate of carriers in the quantum wells of an LED is a useful method since the modulation bandwidth of an LED is related to the carrier decay rate besides the device RC time constant To increase the carrier decay rate in an LED without sacrificing its output power, the technique of surface plasmon (SP) coupling in an LED is useful. In this paper, the increases of modulation bandwidth by reducing mesa size, decreasing active layer thickness, and inducing SP coupling in blue- and green-emitting LEDs are illustrated. The results are demonstrated by comparing three different LED surface structures, including bare p-type surface, GaZnO current spreading layer, and Ag nanoparticles (NPs) for inducing SP coupling. In a single-quantum-well, blue-emitting LED with a circular mesa of 10 microns in radius, SP coupling results in a modulation bandwidth of 528.8 MHz, which is believed to be the record-high level. A smaller RC time constant can lead to a higher modulation bandwidth. However, when the RC time constant is smaller than ~0.2 ns, its effect on modulation bandwidth saturates. The dependencies of modulation bandwidth on injected current density and carrier decay time confirm that the modulation bandwidth is essentially inversely proportional to a time constant, which is inversely proportional to the square-root of carrier decay rate and injected current density.

10124-22, Session 5

Enhancement of internal quantum efficiency of GaN:Eu-based red light emitters through surface plasmon engineering

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Europium doped Gallium Nitride (GaN:Eu) has been used as a potential candidate for red light emission. Both resonant and above-bandgap optical excitation as well as electrical excitation of GaN:Eu system have revealed emission sites located at ~620 nm. Despite the red luminescence of these sites, the internal quantum efficiency (IQE) of the GaN:Eu system is low. A possible solution to increase the IQE is through the enhancement of radiative efficiency of Eu+3 ions in the GaN host. It is known that by utilizing surface plasmons (SP) the radiative efficiency of a system can be enhanced due to increase of photon density states near the SP frequency through Purcell factor. Thus, by tuning the SP frequency close to the frequency of the emitted photon from Eu+3 ions, the IQE of GaN:Eu system is expected to increase.

In this work we examine the effect of several metals (Au, Ag, TiN, Co) and their combinations as potential plasmonic materials for GaN:Eu system for red light emission. Theoretical investigation shows that among those, TiN exhibits high Purcell factor at ~2.0 eV via tuning the thickness of TiN layer on top of the GaN:Eu material. In complementary to theoretical work, we use sputtering to deposit TiN films on top of GaN:Eu grown on double sided polished sapphire. Through photoluminescence studies we investigate the impact of different TiN layer thicknesses on the IQE of GaN:Eu system. The use of TiN as plasmonic material in the red spectra regime can significantly increase the IQE of GaN:Eu system.

10124-23, Session 5

Resonant cavity bright red light-emitting diodes based on dielectric passive cavity structures

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Combined semiconductor–dielectric light–emitting diodes (LEDs) at 610 nm are proposed, where the active semiconductor epitaxial structure contains a distributed Bragg reflector (DBR), into which an active zone is introduced. On top of the semiconductor template a dielectric structure containing a resonant dielectric cavity and a top dielectric DBR is deposited. Such resonant cavity structure is a passive cavity structure [1], in which the intensity maximum of the resonant optical mode is located in a passive dielectric layer. Application of the passive cavity concept to vertical cavity surface emitting lasers (VCSELs) [2] allows efficient control of the temperature behavior of the resonance wavelength. In the present paper the application of the passive cavity concept to LEDs is considered, where another advantage is explored. Namely, the passive cavity structure allows, on the one hand, deep patterning including selective etching of the multilayer dielectric coating down to the semiconductor template, where the etching occurs through the passive dielectric cavity, in which intensity of the optical mode is maximum, and, on the other hand, no etching occurs through the active zone and does not create any damage. As an example structure, a passive cavity LED has been modeled, containing a semiconductor DBR formed of Ga(1–x)Al(x)As layers with alternating Al content, multiple quantum wells of Ga(1–y)In(y)P emitting orange light at ~610 nm, a passive dielectric SiO2 cavity and a top dielectric Ta2O5/SiO2 DBR. For the patterning both cylindrically–symmetric structures with concentration ring patterns and periodic hexagonally–symmetric lateral photonic crystals formed of holes have been modeled. It has been demonstrated that the extraction coefficient of light to the air, which is ~2% for a device with a flat surface without dielectric, can be increased up to 8% or higher due to patterning if the pattering periodicity is at ~1 μm or less, in case of a conventional simple bottom semiconductor Al0.5Ga0.5As–AlAs DBR. By using a bottom DBR with selectively oxidized Al(Ga)As layers aimed to reflect light at a broad range of angles, the extraction coefficient can exceed 50%. Furthermore, patterning of dielectric structures by lateral photonic crystals of various type allows efficient control and narrowing of the far field diagram of light emission. Consequently, high efficiency high brightness LEDs and LED arrays can be engineered and manufactured.

[1] N. Ledentsov, “Optoelectronic Device and Method of Making Same”, US Patent 8,472,496, filed July 6, 2010, issued June 25, 2013

[2] V. Shchukin, et al. “Passive Cavity Surface–Emitting Lasers: Option of Temperature–Insensitive Lasing Wavelength for Uncooled Dense Wavelength Division Multiplexing Systems”, Proc. SPIE, vol. 9766, paper 976609.

10124-24, Session 6

AlGaN nanowire light-emitting diodes: breaking the efficiency bottleneck of deep ultraviolet light sources *(Invited Paper)*

Zetian Mi, Univ. of Michigan (United States); Songrui Zhao, Sharif M. Sadaf, McGill Univ. (Canada)

To date, it has remained challenging to achieve high efficiency AlGaN nanowire LEDs operating in the UV-C band, which has been limited by the presence of large densities of defects and dislocations, the inefficient p-type conduction, and the unique TM polarized light emission in Al-rich AlGaN. In this context, we have investigated the epitaxy and performance

characteristics of Al-rich AlGaN nanowire LEDs, which promise to overcome the efficiency bottleneck of deep UV light sources.

In this experiment, Al(Ga)N nanowire LED structures are grown on Si substrate by radio-frequency plasma-assisted molecular beam epitaxy. The LED structure consists of Al(Ga)N double-heterojunction and n-GaN and p-Ga(Al)N contact layers. Under nitrogen-rich growth conditions, the formation of quantum dot-like nanostructures in nearly defect-free AlGaN nanowires is observed, which leads to strong carrier confinement and relatively high luminescence efficiency (~80%) at room temperature. The fabrication of AlGaN nanowire LEDs involves the use of standard photolithography and contact metallization techniques. By varying the growth conditions, electroluminescence emission in the wavelength range of 207 to 280 nm has been demonstrated. The device show excellent electrical efficiency (up to 85%), due to the significantly enhanced Mg-dopant incorporation in AlGaN nanowires and the resulting efficient hole hopping conduction in the Mg impurity band. The incorporation of metal/semiconductor tunnel junction to achieve high power operation in the wavelength range of 240 nm is also demonstrated and will be reported.

10124-25, Session 6

In-situ metrology in multiwafer reactors during MOVPE of UV-LED structures

(Invited Paper)

Arne Knauer, Frank Brunner, Tim Kolbe, Sylvia Hagedorn, Viola Kueller, Markus Weyers, Ferdinand-Braun-Institut (Germany)

UV-LEDs are of great interest for applications like disinfection, gas sensing, and phototherapy. The cost sensitive LEDs are commonly grown by MOVPE on transparent AlN/sapphire templates. The large thermal and lattice mismatch between AlN and sapphire generates a very high dislocation density (DD) and causes big challenges in strain management. The threading dislocation density should be reduced to the order of low 108cm-2 for high internal efficiency of the AlGaN based UV-LED structures. The TDD will be reduced mainly by dislocation annihilation during the growth of thick Al(Ga)N layers, which is a challenge in terms of strain management.

We present how in-situ reflectometry and curvature measurement (EpiCurveTT@LayTec) in commercial multiwafer growth reactors helps to optimize the growth processes concerning growth rates, surface roughening and avoidance of layer cracking on 2inch substrates and enhance the reproducibility of epitaxial growth. The growth of up to 3 µm thick planar AlN templates and up-to 10 µm thick AlN/sapphire templates by epitaxial lateral overgrowth of stripe patterned templates for UV-C LED structures will be highlighted. The implementation of different types of AlN/GaN superlattices for the subsequent growth of up to 5µm thick Al0.5Ga0.5N layer for UVB LED structures will be shown. Correlations to ex-situ measurements like X-ray diffraction and TEM analysis of defects in the LED structures will be shown.

Some challenges of in-situ control through very narrow viewports as in Close Coupled Showerhead reactors will be discussed as well as the influence of silicon doping on curvature and dislocation density in Al(Ga)N layers.

10124-26, Session 6

Plasmonics toward high-efficiency LEDs from the visible to the deep-UV region

(Invited Paper)

Koichi Okamoto, Kyushu Univ. (Japan); Mitsuru Funato, Yoichi Kawakami, Kyoto Univ. (Japan); Narihito Okada, Kazuyuki Tadatomo, Yamaguchi Univ. (Japan); Kaoru Tamada, Kyushu Univ. (Japan)

Plasmonics is one very promising method to improve the emission efficiencies of light-emitting diodes (LEDs). I present here the recent progress of our approach toward development of the high-efficiency plasmonic LED devices. We obtained the enhancement of the electroluminescence from the fabricated plasmonic LED device structure by employing the very thin p+GaN layer. The further enhancements should be achievable by optimization of the metal and device structures. Next important challenge is to extend this method from the visible to the deep UV region. By using Aluminum, we already obtained the enhancements of emissions at ~260 nm from AlGaN/AlN quantum wells. We succeeded to control the SP resonance by using the various metal nanostructures. We found that the Ta nanoparticles (NPs) have strong localized surface plasmon resonance (LSPR) at around 200 nm, which is the shortest wavelength in any other metal NPs. Moreover, we observed the peak splitting of extinction spectra when the Ag NPs were placed on a metal substrate. By using this structure with Al NPs, very strong and sharp resonance peak was obtained at 156 nm by the FDTD simulation. As far as we know, this is the LSPR spectrum which has the shortest peak wavelength at Ultra-Deep-UV region. These LSPR spectra in the deep-UV regions presented here would be useful to enhance deep UV emissions of super wide bandgap materials such as AlGaN/AlN and also mixed oxide semiconductors. We believe that our approaches based on ultra-deep UV plasmonics would bring high efficiency ultra-deep UV light sources.

10124-27, Session 6

Influence of interconnection on the long-term reliability of UV-LED packages

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Influence of interconnection on the long term reliability of UV-LED packages

High power LEDs have conquered the mass market in recent years. Besides the main development focus to achieve higher productivity in the field of visible semiconductor LED processing, the wavelength range is further enhanced by active research and development in the direction of UVA / UVB / UVC. UVB and UVC-LEDs are new and promising due to their numerous advantages compared to conventional mercury discharge lamps and xenon sources, which show broad spectrums with many emission peaks over a wide range of wavelengths. UV-LEDs emit in a near range of one single emission peak with a width (FWHM) below 15 nm. Furthermore, the UV-LED size is in the range of a few hundred microns and offers a high potential of significant system miniaturization. Of course, LED efficiency, lifetime and output power have to be increased.

One lifetime limiting characteristic of UVB/UVC- LED is the very high thermal stress in the chip resulting from the higher forward voltages (6-10 V @ 350 mA), the lower external quantum efficiency below 3 % (most of the power disappears as heat) and the Rth of conventional LED packages beeing not able to dissipate these large amounts of heat for spreading. Beside the circuit boards and submounts which should have maximum thermal conductivity, the dimension of contacts as well as the interconnection of UV-LED to the submount/package determinates the resolvable amount of heat.

In the paper different innovative interconnection techniques for UVB/UVC-LED systems will be discussed focused on the optimization of thermal conductivity as well as the reduction of assembly costs. Results on thermal simulation for the optimal contact dimensions and interconnections will be given. In addition, these theoretical results will be compared with results on thermographic images and videos on real UV-LED packages in order to give recommendations for optimal UV-LED assembly.

10124-28, Session 6

Defect generation in deep-UV AlGaN-based LEDs investigated by electrical and spectroscopic characterisation

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(In)AlGaN-based UV-B light-emitting diodes (LEDs) are promising candidates to replace conventional ultraviolet sources in various applications thanks to their low operation voltage and adjustable emission wavelength. However, these devices can show a relatively fast degradation during operation. It is widely discussed that stress may induce an increase in density or redistribution of point defects, like nitrogen vacancies or Mg-H defect complexes, which can reduce the internal quantum efficiency of the devices.

The aim of this paper is to describe an extensive analysis of the degradation of (In)AlGaN-based UV-B LEDs submitted to constant current stress, and to investigate the impact of defects in changing the electro-optical performance of the devices.

The study is based on combined electrical and optical characterization, deep-level transient- (DLTS) and photocurrent spectroscopy. The results of this analysis demonstrate that UV-B LEDs show a decrease of the optical power during stress, which is more pronounced at low measuring current levels. Such a behavior indicates that the degradation is related to an increase of Shockley-Read-Hall (SRH) non-radiative recombination. DLTS measurements allowed the identification of three defect-related signatures correlated to the degradation of the optical and electrical characteristics. For example, one can be associated to the decrease of the drive voltage and ascribed to the increase of p-type conductivity by activation of Mg acceptors. By means of photocurrent spectroscopy, it was possible to localize the energetic position of the trap states behaving as non-radiative recombination centers, which is 2-2.5 eV below the conduction band and thus close to the mid-gap.

10124-29, Session 6

Demonstration of UV LED versatility when paired with molded UV transmitting glass optics to produce optimized irradiance patterns

Brian S. Jasenak, Kopp Glass Inc (United States)

With the advent of UV LEDs, light can be refracted to produce optimized irradiance patterns for demanding applications—from UV curing to sterilization to inspection. The directional light output of LEDs provides opportunities to use optics and lighting for applications not previously possible. However, adoption has been slow in some applications due to challenges related to UV LED's light distribution pattern and intensity. Opportunities exist to bring innovative UV LED products to market through the use of UV transmitting glass optics. Uniform illumination of 2D and 3D surfaces is possible when LEDs are combined with UV glass optics.

In this study, simulated modeling was performed to demonstrate the enhanced irradiance patterns such as improved uniformity and increased irradiance that can be achieved when optics are applied to UV LEDs. The benefits of pairing these glass optics with UV LEDs will be demonstrated for generalized application uses such as UV light conveyor systems or contoured surface illumination. Potential system benefits will also be reviewed including increased product quality, differentiated system configuration, faster throughput, lower maintenance and increased system lifetimes due to the use of optics with LED arrays.

10124-30, Session 7

Role of alloy fluctuations in green gap and efficiency droop of visible nitride LEDs *(Invited Paper)*

Matthias Auf der Maur, Univ. degli Studi di Roma “Tor Vergata” (Italy); Alessandro Pecchia, Consiglio Nazionale delle Ricerche, Istituto per lo Studio dei Materiali Nanostrutturati (Italy); Gabriele Penazzi, Univ. Bremen (Germany); Walter Rodrigues, Aldo Di Carlo, Univ. degli Studi di Roma “Tor Vergata” (Italy)

Green III-nitride LEDs suffer from a systematic efficiency penalty compared to blue LEDs, hampering the realization of wight light emission by direct color mixing. By a combination of semi-classical and atomistic simulations we show, that part of the observed drop in efficiency can be attributed to the statistical disorder in the InGaN alloy in the quantum well of such devices. By comparison with measured data, it is shown that the theoretical model correctly reproduces the experimentally observed wavelength dependence of the radiative recombination coefficient. We also show assuming some spatial non-uniformity in the alloy distribution may explain further observed data like spectral width and s-shaped peak wavelength versus temperature curves.

10124-31, Session 7

Spatial and compositional dependence of deep-level defects in InGaN LEDs *(Invited Paper)*

Andrew M. Armstrong, Mary H. Crawford, Daniel D. Koleske, Sandia National Labs. (United States); Erik C. Nelson, Isaac Wildeson, Parijat Deb, Lumileds, LLC (United States)

Efficiency droop and the green gap are challenges to InGaN/GaN light emitting diodes (LEDs). Defects have been suggested to contribute to both effects, so understanding the origin of defects and their impact on LED performance is important to improving efficiency. This talk describes the use of deep level optical spectroscopy (DLOS) to characterize deep level defects in quantum well (QW) and quantum barrier (QB) regions of InGaN LEDs. The spatial dependence of deep level defect density in the MQW region and the evolution of QW deep level defects with indium alloying will be discussed.

10124-32, Session 7

Excitation-dependent quenching in LED phosphors

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Schmidt, Lumileds Germany GmbH (Germany); Fahong Jin, Danielle R. Chamberlin, Lumileds, LLC (United States); Helmut Bechtel, Lumileds Germany GmbH (Germany); Alice Liu, Lumileds, LLC (United States)

The decrease in white LED efficiency with drive is a major design constraint in Solid State Lighting. This decrease, commonly known as "droop", forces a trade-off between energy efficiency, form and cost of a lighting system, as customers and regulators set higher expectations for energy savings and system performance. Historically, the technology community has been focused on understanding and mitigating the droop in the active region of InGaN-based pump LEDs. In this work we turn attention to efficiency quenching (droop) in common LED phosphor materials under high levels of excitation. We characterize the droop in phosphors at different temperatures by employing pulsed optical excitation to minimize additional heating. We then study the dependence of the droop on activator concentration by focusing on Eu 2+ doped red-luminescent nitride powders. We find that the rate of quenching with excitation is temperature dependent. At a given temperature, the efficiency droop is well predicted by including a non-linear relaxation rate term locally proportional to the square of concentration of excited Eu2+ with the proportionality coefficient independent of activator concentration. This gives us insight into possible basic mechanism responsible for the excitation dependence of the quenching. We then quantify the impact of the droop in phosphors on integral LED performance and discuss means for mitigation through material and device engineering.

10124-33, Session 7

Luminescence distribution in the multi quantum well region of III-nitride light emitting diodes

Friedhard Roemer, Bernd Witzigmann, Univ. Kassel (Germany)

The distribution of the luminescence in a multi quantum well (MQW) III-nitride light emitting diode (LED) is critical for the droop. A homogeneous current distribution is targeted to reduce the relative contribution of the Auger recombination. Though the current distribution is opaque to the internal quantum efficiency characterization we demonstrate by carrier transport simulations that there is a relation to the current versus voltage (I/V) characteristic of the diode.

The carrier transport simulator is based on a multi population drift-diffusion approach which has been enhanced with an effective potential model to account for the MQW barrier tunneling. The enhanced transport model has been verified and calibrated with the luminescence spectra of multi color LEDs.

Since changes in the I/V characteristic are rather small we investigate the ideality as a measure for its gradient instead. It is demonstrated that the non-ideal I/V characteristic of a III-nitride MQW LED near the efficiency maximum can be largely attributed to the resistance of the MQW barriers for holes and the scattering of the electrons from the continuum into the quantum wells. The hole scattering as well as the conduction band barriers have a minor impact on the resistance.

A globally homogeneous luminescence distribution is not feasible due to the asymmetry of the electron and hole transport. We demonstrate that a balanced distribution is enabled by the shift of the current load from the n-side to the p-side quantum well with increasing current. This shift is supported by a low scattering resistance of the p-side quantum well. Therefore the homogeneous current distribution is seen through a strong change of the current load and a lower ideality compared to an inhomogeneous distribution.

10124-34, Session 7

Elimination of resistive losses in large-area LEDs by new diffusion-driven devices

Pyry Kivisaari, Lund Univ. (Sweden); Iurii Kim, Sami Suihkonen, Jani Oksanen, Aalto Univ. (Finland)

III-N light-emitting diodes (LEDs) suffer from resistive losses and current crowding in the n-type current-spreading layer, leading to saturation of the current-voltage curve already at relatively small currents. Bulk GaN substrates enable making thicker n-type GaN layers and thereby partly alleviate the problem, but bulk GaN substrates are still prohibitively expensive for most applications. In this work we investigate how diffusion-driven current transport (DDCT) can be combined with selective-area (re) growth (SAG) of GaN to eliminate the resistive losses of large-area LEDs without the need for thick current-spreading layers. Using SAG, we can realize laterally doped periodic n- and p-type regions that inject electrons and holes to an underlying multi-quantum well (MQW) by diffusion. We show that optimization of the structure leads to equally efficient low current operation as in conventional LED devices. More importantly, due to the large density of the p- and n- regions, we can also achieve nearly resistance-free large-current operation of LEDs with the additional advantage that the MQW does not need to be pierced to enable electrical contacting. In addition to simulations, we report experimental results of single-quantum well samples overgrown with doped SAG GaN layers. The photoluminescence measurements show that SAG of the doped layers does not have harmful effects on the QW emission spectrum, demonstrating that the combination of DDCT and the SAG process can lead to a new and more efficient class of high power light emitters.

10124-35, Session 8

Nanoscale analysis of III-N LED structures using cathodoluminescence and induced conductivity measurements *(Invited Paper)*

Robert W. Martin, Univ. of Strathclyde (United Kingdom)

Analysis of the optical, electrical and physical properties of light-emitting materials with nanoscale spatial resolution provides informs the understanding and improvement of devices. The use of correlated measurements in the scanning electron microscope and electron probe microanalyser to achieve this. Combinations of cathodoluminescence (CL), X-ray microanalysis, electron beam induced current (EBIC), electron back-scattered diffraction (EBSD) and electron channeling contrast imaging (ECCI) is described. These provide structural information at nm scale and optical information down to 10s of nm and at wavelengths beyond the AlN bandgap. Results will be presented from a range of nanoscale light-emitting structures built using III-N materials.

10124-36, Session 8

Structural and copositional multiprobe investigations of AlInGaN semiconductor structures and core-shell nanorod LEDs *(Invited Paper)*

Florian F. Krause, Marco Schowalter, Univ. Bremen (Germany); Marcus Müller, Otto-von-Guericke Univ. Magdeburg (Germany); Tilman Schimpke, OSRAM Opto Semiconductors GmbH (Germany); Sebastian Metzner, Otto-von-Guericke-Univ. Magdeburg (Germany); Joachim Hertkorn, OSRAM Opto Semiconductors GmbH (Germany); Jan-Philipp Ahl, OSRAM Opto Semiconductors

GmbH (Germany); Frank Bertram, Otto-von-Guericke-Univ. Magdeburg (Germany); Thorsten Mehrtens, Univ. Bremen (Germany); Peter Veit, Otto-von-Guericke-Univ. Magdeburg (Germany); Knut Müller-Caspary, Univ. Bremen (Germany); Karl Engl, Martin Strassburg, OSRAM Opto Semiconductors GmbH (Germany); Jürgen H. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany); Andreas Rosenauer, Univ. Bremen (Germany)

The electronic properties of semiconductor devices depend not only significantly on the composition but also on the compositional homogeneity of the alloy. A versatile method to investigate this homogeneity is high-angle annular dark field (HAADF) scanning transmission electron microscopy (STEM). By quantifying the agreement of the statistics of atomic column intensities from experiment and from simulations of an ideal random alloy and employing statistical tests an assessment of potential compositional fluctuations is possible.

The method was used on the AlInGaN material system, which has attracted attention for the construction of optoelectronic devices, benefitting from its additional compositional degree of freedom. AlInGaN layers with different compositions grown by metal-organic vapor phase epitaxy were investigated. Though HAADF STEM evaluation only allows for the reduction of possible combinations of indium and aluminum concentrations to the proximity of isolines in the two-dimensional composition space, the statistical evaluation can asses the homogeneity. The investigated samples are found to be fully homogeneous with high significance. The statistical power of the tests is validated by comparison to additional simulations of indium-rich clusters, which show significant deviation from the distribution of a random alloy. The investigations thus allow ruling out indium clustering.

The method was furthermore used to investigate the homogeneity of the active InGaN layer in three-dimensional nitride based core-shell nanorods, which are promising candidates to achieve highly efficient optoelectronic devices. In a combined nanoscopic study by highly spatially resolved low-temperature cathodoluminescence (CL) spectroscopy performed in STEM and HAADF STEM, strong localisation effects of the excitonic emission were found, which could be directly related to inhomogeneities of the In concentration.

10124-37, Session 8

Recent advances in nanostructure micro LEDs for RGB microdisplays

Richard P. Schneider Jr., Stephon Fan, Daniel Thompson, Mitch Jansen, Fariba Danesh, GLO-USA, Inc. (United States); Michael E. Coltrin, Sandia National Labs. (United States); Bo Monemar, Jonas Ohlsson, Zhaoxia Bi, Kristian Storm, Lund Univ. (Sweden); Rafal Ciechonski, Glo AB (Sweden); Lars Samuelson, Lund Univ. (Sweden) and Glo AB (Sweden)

We report on InGaN/GaN nanowire-based micro LEDs (nLEDs) emitting across the entire spectral region required for RGB microdisplays. These nLEDs have been proposed as being particularly advantageous for DV applications [1], since they exhibit highest external quantum efficiency (EQE) at current densities <<1A/cm2, or roughly 2 orders of magnitude lower current density than equivalently sized "planar" LEDs. Highest EQE is demonstrated for green nLEDs, emitting at ~520nm. We have also demonstrated blue nLEDs, emitting at ~470nm, and InGaN-based red nLEDs, emitting at ~620nm. The latter demonstration of display-class red nanowire LEDs is, to our knowledge, the first of its kind. Here the unique geometry of nanowires enables the accommodation of very high strain in the InGaN active region (expected to be on the order of 5%) without the formation of defects.

In another approach to achieve functional InGaN-based red micro LEDs, we have demonstrated c-oriented and dislocation-free InGaN-based nano-templates, upon which high In-content LED epitaxy can be grown without the high strain and defect densities which otherwise plague planar red LED materials based on InGaN. We will here present green as well as red-emitting c-oriented InGaN LEDs formed on top of such InGaN templates.

[1] B. Monemar, B. Jonas Ohlsson, N. F. Gardner and L. Samualson, "Nanowire-Based Visible Light Emitters, Present Status and Outlook", appearing in "Semiconductor Nanowires II: Properties and Applications", Ed. S. A. Dayeh, A. F. I Morral and C. Jagadish, Semiconductors and Semimetals 94, 227-272 (2016).

10124-38, Session 8

Improvement of thermal stability of type-II composition-gradient thick-shell quantum dots green light-emitting diodes

Hsin-Chieh Yu, Hoang-Tuan Vu, National Cheng Kung Univ. (Taiwan)

A significant improvement of thermal stability of green quantum dot light emitting diodes (QLEDs) was demonstrated in this report by using composition-gradient thick-shell CdSe@ZnS/ZnS quantum dots (QDs). According to the experiment results the electroluminescence (EL) intensity of the fabricated type-II QLEDs with thick-shell structure only decreased 3% even when the operation temperature was elevated to 110 ?. And the current efficiency roll-off effect could be improved nearly 200% under higher current density condition. More specifically, the thermal stability improvement of QLEDs by using composition-gradient thick-shell QDs was investigated and analyzed according to the EL characteristics of the fabricated devices for the first time. Thick-shell QDs with low defective structure could effectively prevent the electron-hole pairs from nonradiative Auger recombination and avoid the thermal-stress-induced expansion at elevated temperatures and higher driving current. As a result, 97 % of the electroluminescent feature could be maintained after the device was thermally-stressed at temperature up to 110 ?. Furthermore, the maximum current efficiency of the thick-shell-device is 10.3 cd/A, which is much higher than 1.57 cd/A for the conventional thin-shell-device. These results indicated that rational design and assembly of QDs is essential for the fabrication of high-performance QLEDs.

10124-39, Session 9

Thermophotonics for ultra-high efficiency visible LEDs (Invited) *(Invited Paper)*

Rajeev J. Ram, Massachusetts Institute of Technology (United States)

The wall-plug efficiency (WPE) of modern LEDs has far surpassed all other forms of lighting and is expected to improve further as the lifetime cost of energy consumption exceeds the manufacturing cost of the devices. This inevitably opens the question about further enhancement towards the conventional limit of unity efficiency. A forward biased light-emitting diode (LED) can work as a heat pump, which pumps lattice heat into the incoherent photon field at the expense of consuming low-entropy electrical power. In this scenario, the LED has an over-unity WPE and exhibits net cooling. In 1957, Tauc pointed out that carriers absorb lattice heat by a Peltier effect at the diode junction. However, researchers had not reported a measurement of WPE>1 until 2012 when our group [Santhanam et al. PRL 2012] demonstrated an infrared GaInAsSb/GaSb LED with a WPE over 200% at 135 ?.

Here, we investigate thermoelectric pumping in wide-bandgap GaN based light-emitting diodes (LEDs). We experimentally demonstrate a thermally enhanced 450 nm GaN LED, in which nearly fourfold light output power is achieved at 615 K (compared to 295 K room temperature operation), with virtually no reduction in the wall-plug efficiency at bias V<??/q. This result suggests the possibility of removing bulky heat sinks in high power LED products. A review of recent high-efficiency GaN LEDs suggests that Peltier thermal pumping plays a more important role in a wide range of modern

LED structures that previously thought – opening a path to even higher efficiency and lower lifetime cost for future lighting.

10124-40, Session 9

Novel contact schemes using highly Ge-doped GaN *(Invited Paper)*

André Strittmatter, Otto-von-Guericke Univ. Magdeburg (Germany)

Recent advances in contact schemes to light emitting devices using highly Ge-doped GaN layers will be presented. In particular, growth of p/n tunnel junctions on top of LED and laser structures by metalorganic vapor phase epitaxy is discussed. Such tunnel junctions are very attractive for large area LEDs as well as for laser diodes as the improve current spreading and reduce absorption losses as the thickness of p-doped GaN layers can be reduced to minimum.

10124-42, Session 9

Efficient metal halide perovskite light-emitting diodes *(Invited Paper)*

Tae-Woo Lee, Seoul National Univ. (Korea, Republic of)

Metal halide perovskites are emerging low-cost emitters with very high color purity (full width at half maximum ~ 20 nm). However, the low electroluminescence efficiency at room temperature originating from exciton dissociation and quenching is a challenge that should be overcome. Here, we introduce problems of perovskites limiting electroluminescence efficiency and present solutions of these problems for achieving high-efficiency perovskite light-emitting diodes (PeLEDs). First, hole injection barrier between ITO anode and perovskite emission layer (EML) should be reduced. Also, exciton quenching at the interface between hole injection layer (HIL) and EML decreases electroluminescence efficiency. We introduced a self-organized buffer hole injection layer (Buf-HIL) to reduce the hole injection barrier and block the exciton quenching at the interface. Furthermore, we found that the formation of metallic lead atoms causes strong exciton quenching, and it was prevented by finely increasing the molar proportion of methylammonium bromide (MABr) by 2 to 7 % in $MAPbBr_3$ solution. Also, we suggest that the efficiency in PeLEDs can be increased by decreasing $MAPbBr_3$ grain sizes and consequently improving uniformity and coverage of $MAPbBr_3$ nanograin layers. Use of an optimized nanocrystal pinning process contributed to the change in the morphology of $MAPbBr_3$ layers from scattered micrometer-sized cuboids to well-packed nanograins with uniform coverage, which greatly reduced leakage current and increased efficiency. Furthermore, A $MAPbBr_3$ film with decreased grain size exhibited a very small exciton diffusion length. Using these strategies, a highly efficient perovskite light-emitting diode was achieved (current efficiency = 42.9 cd/A, external quantum efficiency = 8.53%).

10124-43, Session 10

Progress in LED technology for solid-state lighting *(Invited Paper)*

Jyoti Bhardwaj, Lumileds, LLC (United States)

As solid state lighting adoption moves from bulb socket replacement to system level engineering, luminaire manufacturers are beginning to actualize far greater cost savings through system optimization rather than the simplistic process of component cost pareto management. Indeed, there are an increasing number of applications in which we see major shifts in the value chain in terms of increasing the L1 (LED) and L2 (LED array on PCB) value. The L1 value increase stems from a number of factors ranging from simply higher performing LEDs reducing the LED count, to L1 innovation such as high voltage LEDs, optimizing driver efficiency or to the use of very high luminance LEDs enabling compact optics, allowing not only more design freedom but also cost reduction through space and weight savings. The L2 value increase is realized predominantly through either increasing L2 performance (lumens, lm/W or tight Vf distribution) with the use of algorithms which optimize L1 selection and placement (based on detailed individual LED performance data) and/or through L2 integration of drivers, control electronics, sensors, secondary lens and/or environmental protection, which is also initiating level collapse in the value chain. In this paper we will present the L1 and L2 innovative technologies which are enabling this disruption as well as provide examples of system level benefits using a broad range of applications.

10124-44, Session 10

Miniaturized LEDs for flat-panel displays *(Invited Paper)*

Erich Radauscher, Matthew Meitl, Kanchan Ghosal, Salvatore Bonafede, Carl Prevatte, David Gomez, Tanya Moore, Robert Rotzoll, David Kneeburg, X-Celeprint (United States); Antonio Jose Trindade, Alin Fecioru, Alexandre Chikhaoui, X-Celeprint Ltd. (Ireland); Ron Cok, Christopher A. Bower, X-Celeprint (United States)

Inorganic light emitting diodes serve as bright pixel-level emitters in displays that are very large or very small, from indoor/outdoor video walls with pixel sizes ranging from one to thirty millimeters to micro displays with more than one thousand pixels per inch. Pixel sizes that fall between those ranges, roughly 50 to 500 microns, are some of the most commercially significant ones, including flat panel displays used in smart phones, tablets, and televisions. Flat panel displays that use inorganic LEDs as pixel level emitters (iLED displays) can offer levels of brightness, transparency, and functionality that are difficult to achieve with other flat panel technologies. Cost-effective production of iLED displays requires techniques for precisely arranging sparse arrays of extremely miniaturized devices on a panel substrate, such as transfer printing with an elastomer stamp. Here we present lab-scale demonstrations of transfer printed iLED displays and the processes used to make them. Demonstrations include passive matrix iLED displays that use conventional off-the shelf drive ASICs and active matrix iLED displays that use miniaturized pixel-level control circuits from CMOS wafers. We present a discussion of key considerations in the design and fabrication of highly miniaturized emitters for iLED displays.

10124-45, Session 10

Design of a lighting system with high-power LEDs, large area electronics, and light management structure in the LUMENTILE European project

Luca Carraro, Marcello Simonetta, Guido Benetti, Alessandro Tramonte, Giorgio Capelli, Univ. degli Studi di Pavia (Italy); Mauro Benedetti, Enrico M. Randone, Julight S.r.l. (Italy); Arto Ylisaukko-oja, Kimmo Keränen, VTT Technical Research Ctr. of Finland Ltd. (Finland); Tullio Facchinetti, Guido Giuliani, Univ. degli Studi di Pavia (Italy)

LUMENTILE (LUMinous ElectroNic TILE) is a project funded by the European Commission with the goal of developing a luminous tile with novel functionalities, capable of changing its color and interact with the user. Applications include interior/exterior tile for walls and floors covering, high-efficiency luminaries, and advertising under the form of giant video screens. High overall electrical efficiency of the tile is mandatory, as several millions of square meters are foreseen to be installed each year.

Demand is for high uniformity of the illumination of the top tile surface, and for high optical extraction efficiency. These features are achieved by smart

light management, using a new approach based on light guiding slab and spatially selective light extraction obtained using both diffusion and/or reflection from the top and bottom interfaces of the optical layer. Planar and edge configurations for the RGB LEDs are considered and compared.

A square shape with side length from 20cm to 60cm is considered for the tiles. The electronic circuit layout must optimize the electrical efficiency, and be compatible with low-cost roll-to-roll production on flexible substrates. LED heat management is tackled by using dedicated solutions that allow operation in thermally harsh environment.

An approach based on OLEDs has also been considered, still needing improvement on emitted power and ruggedness.

10124-46, Session 10

High-power LEDs for non-contact energy transfer

Hal Gokturk, Ecoken (United States)

As rechargeable batteries proliferate from smart phones to electric vehicles, recharging them without attaching cables and even without user intervention is becoming a desirable feature. Some makers are responding to this need by equipping products with photovoltaic (PV) modules, though daylight charging provides limited energy. What is proposed in this paper is the utilization of a high power LED as the energy source for non-contact charging via PV.

Blue LED used in high brightness white LEDs would be a suitable light source for this application. It has peak emission wavelength of 450 nm, operating power of more than 10 W, efficiency up to 80%. It can be focused to a beam of small divergence angle (~25°) with built-in optics. A 10 W LED can produce light intensity equivalent to average daylight intensity of 0.2 kW/m2 at a distance of ~5 cm. Multiple LEDs can be combined into an array that can provide light intensity far exceeding that of daylight.

The PV module is assumed to be a silicon solar cell with a conversion efficiency of 15-20% for daylight. Blue LED has an average photon energy of 2.76 eV which is more than twice the bandgap of Si. To optimize energy transfer from the LED to the PV module, blue photons must be down-converted to near infrared photons with a method such as given in [1]. PV conversion efficiencies up to 50% is achievable with this arrangement.

[1] H. Gokturk, "Down Conversion of Solar Photons Using Alkali Vapors," SPIE Photonics West, OPTO16, San Francisco

10124-48, Session 10

Development of high-performance (0001) LEDs: tunnel junctions and green LEDs

(Invited Paper)

James S. Speck, Univ. of California, Santa Barbara (United States)

In this presentation, we highlight two recent areas of development of high performance c-plane GaN-based LEDs

Tunnel Junctions: Efficient tunnel junctions (TJ) provide a means of carrier conversion between p-type and n?type material in semiconductor devices and are potentially advantageous for the III?Nitride material system, where the poor conductivity of p?GaN impacts the design and efficiency of light emitting and laser diodes (LEDs and LDs). We have developed a technologically viable hybrid growth approach that involves growing the active region of devices and top p?GaN layers by the standard (MOCVD) growth technique, followed by growth of the highly doped n-side of the TJ by ammonia?assisted molecular beam epitaxy. We have successfully realized high performance VCSELS, edge emitting laser diodes, and LEDs. For LEDs the high conductivity and low optical loss of n-type GaN enables new designs that effectively increase the light extraction efficiency. We present c-plane 450 nm LEDs with a peak EQE and WPE of 76% and 73%, respectively.

Green LEDs: We demonstrate very high luminous efficacy MOCVD growth of green light-emitting diodes that employ high temperature InGaN QW growth immediately followed by an Al0.30Ga0.70N cap layer and then a higher temperature GaN barrier. The peak external quantum efficiency and luminous efficacies were 44.3% and 239 lm/W, respectively.

10124-47, Session PWed

LED-based optical sensing of COD and chlorophyll-a

Seon Hoon Kim, Tae Un Kim, Hyun Chul Ki, Haeng Yun Jung, Jung Woon Lim, Doo Gun Kim, Korea Photonics Technology Institute (Korea, Republic of)

We have developed a LED based optical sensor system to measure the concentrations of COD and Chlorophyll-a in the seawater. A red tide is an algal bloom which results from a combination of environmental factors including available nutrients, temperature, sunlight, ecosystem disturbance and the water chemistry. It may cause harm through the production of toxins or by their accumulated biomass. This harmful algae bloom can have a serious impact on human health, wildlife, marine ecosystems, fisheries, and coastal aesthetics. A various organic matter is known as one of the factors that cause red tides in the ocean. So It is necessary to understand the relationships between the concentrations of organic matter and Chlorophyll-a. This study demonstrates the use of LED based optical spectroscopies, such as absorption spectrophotometry and fluorescence spectroscopy, to measure the concentrations of COD and Chlorophyll-a simultaneously. The sensor system uses a LED of the 405 nm wavelength to excite chlorophyll-a and measures fluorescence using a photomultiplier tube with the 685 nm band-pass filter of 40 nm band-width. Also, it uses a LED of the 290 nm wavelength through the seawater sample and measures absorbance using a photomultiplier tube with the 292 nm band-pass filter of 27 nm band-width.

10124-49, Session PWed

Spatially-resolved evaluation of surface-plasmon-coupled photoluminescence-enhancement of InGaN/GaN quantum wells

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We have reported that the photoluminescence (PL) from InGaN quantum wells (QWs) with silver coating was highly enhanced by the surface plasmon (SP) resonance1. In order to understand the enhancement mechanism, here we report the spatially resolved evaluation of the SP coupled PL enhancement by using the microscopic PL mapping.

50-nm-thick of Ag films were deposited onto half of the blue or green emitting InGaN/GaN QWs. PL peak intensity and peak wavelength mapping images were obtained from the silver coated and the un-coated part of the samples. It is known that PL peak intensity and PL peak wavelength have clear correlations for InGaN/GaN QWs by exciton localization process or charge separation process of the quantum confined Stark effect (QCSE). The both processes bring red shift to the emission wavelength2. We found that the PL intensities were increased more than 10 times and the relationships between the peak intensity and wavelength were completely changed by the silver film. We also found that the PL peak wavelength for both samples were shifted into shorter wavelength. This peak shift should be due to the energy transfer from the excitons in InGaN layers to SP polariton. If this process is much faster than the exciton localization and the QCSE processes, the both effect was canceled and the PL spectra should be blue-shifted.

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2?K. Okamoto and Y. Kawakami, IEEE J. Sel. Top. Quantum Electron, 15, 1199 (2009).

10124-50, Session PWed

Light-emitting nanolattices with enhanced brightness

Ryan C. Ng, California Institute of Technology (United States); Rajib Mandal, Rebecca Anthony, Michigan State Univ. (United States); Julia R. Greer, California Institute of Technology (United States)

Three-dimensional (3D) photonic crystals have potential in solid state lighting applications due to their advantages over conventional planar thin film devices. Periodicity in a photonic crystal structure enables engineering of the density of states to improve spontaneous light emission according to Fermi's golden rule. Unlike planar thin films, which suffer significantly from total internal reflection, a 3D architecture structure is more distributed in space with many non-flat interfaces, which facilitates a substantial enhancement in light extraction. We demonstrate the fabrication of a 3D nanolattice with octahedron geometry and mid-IR band gap that utilizes luminescing silicon nanocrystals as active media with an aluminum cathode and ITO anode towards the realization of a 3D light emitting device. The developed fabrication procedure allows charge to pass through the nanolattice between two contacts for electroluminescence. These initial fabrication efforts suggest 3D architected nanolattice devices are realizable and can reach greater efficiencies than planar devices. Future work will explore band gap tunability attained by mechanically straining the structure, first because the strain built up within the active layer leads to exciton localization, which shifts the electronic band gap, and secondly because mechanical strain changes the periodicity within the photonic crystal, which causes a shift in the optical band gap.

10124-51, Session PWed

Simulation of multi-element multispectral UV radiation source for optical-electronic system of minerals luminescence analysis

Vladimir S. Peretiagin, Igor Kantemir, ITMO Univ. (Russian Federation); Timofey K. Korolev, ITMO University (Russian Federation)

The problems of development poor, off-balance sheet deposits become more and more actual with the rapid depletion of solid minerals reserves. There is a significant amount of mineral ore enrichment methods, and radiometric methods are ones of the most promising at the moment. Method of photoluminescence is one of them. Nevertheless this method is used very limitedly in mining industry for several reasons.

Firstly, the UV luminescence characters of the useful minerals and of associated minerals are often very similar to each other. The second reason is associated with the first. It lies in the fact that there are no radiation sources for excitation of selective UV luminescence of minerals with opportunity to analyze a large number of its informative parameters.

The present work is devoted to the development of special UV radiation source designed for the solution problem of analysis and sorting minerals by their selective luminescence.

This paper presents a description of multielement multispectral UV radiation source based on radiating diodes, as well as a description of the results of its experimental studies conducted on samples of muscovite, galena, amber, etc. Such factors as the spectral component, power settings, spatial and energy parameters of radiation diodes included in the developed source were taken into account at creation of this radiation source.

Results obtained can be used, for example, in mineralogy for effective study the physical properties of minerals. In addition, approaches to multielement UV radiation sources modeling may be in demand for not destroying control of different products and materials, in medicine, for quality control of food products and others.

10124-52, Session PWed

Effect of various insertion layers on the external quantum efficiency of GaInN light-emitting diodes

Jaehee Cho, Chonbuk National Univ. (Korea, Republic of); E. Fred Schubert, Rensselaer Polytechnic Institute (United States)

In this study, the effect of various insertion layers on the external quantum efficiency (EQE) of GaInN light-emitting diodes (LEDs) is investigated. First, we found that the EQE of a GaInN LED is improved by inserting a p-type ZnO layer between the indium tin oxide electrode and the p-type GaN layer. Through the discussion of several hypotheses for the EQE improvement in the LED with the ZnO layer, it is concluded that higher hole injection efficiency and better electron confinement can explain the EQE improvement. The device simulations support well the experimental results, showing that the EQE is sensitive to the polarization sheet charge density at the interface between the last quantum barrier and electron-blocking layer. Secondly, an LED with a p-type GaInN spacer layer located between an undoped GaN spacer layer and the p-type AlGaN electron-blocking layer is found to have comparable peak efficiency but less efficiency droop when the crystal quality of the p-type GaInN spacer layer is well-controlled by lowering the growth temperature and by using a suitable indium composition and magnesium doping concentration. Above all, all LED samples with the p-type spacer layer show a smaller efficiency droop compared to a reference LED with an undoped GaN spacer layer.

10124-53, Session PWed

Polarization resolved grazing angle scatterometry for in-situ monitoring of roughness for diffusers for light-emitting device manufacturing

Wojciech J Walecki, Peter S Walecki, Eve S Walecki, Abigail S Walecki, Sunrise Optical LLC (United States)

Novel metrology tool for in-situ characterization of Light Emitting Device diffusers is presented. The tool measures the total integrated scattering when measuring forward, or back-reflection at very large angles of incidence. The tool is insensitive to vibrations and stray light. We discuss polarization resolved data and characterize our technique using NIST traceable standards. We discuss it's applications to semiconductor manufacturing.

The grazing angle reflection measurements were subject of radar [1], semiconductor [2], machine vision [3], space [4], traffic materials [5], and theoretical research [6]. The grazing angle forward reflection metrology was reported by us earlier [7], however, we are not aware of the fully polarization resolved grazing angle back-reflection metrology of roughness of Light Emitting Device diffusers.

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polarization data from unresolved images. Diss. UNIVERSITY OF DENVER, 2015.

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10124-54, Session PWed

Controlled radiation source to stimulate growth and ripening of cultural plants

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Today the development in the field of plant lighting causes a great interest in the sphere of agriculture and agricultural industry. The topical issue of effective year-round cultivation of different cultures correlates to accessibility of implementation.

Existing systems and devices intended for additional lighting of cultural plants use the minimum quantity of peaks in spectral content of the radiation sources (RS). So, there is no way to receive fully all range of wavelengths correlated to a natural source of radiation (the Sun) for the full-fledged growth and development of a plant.

Theoretical researches of optical radiation influence on photobiological processes of growth and development of cultural plants showed that the area of optical radiation having the major substrate-regulatory importance at plants is in boundaries of 280-750 nanometers. In this area the ranges with certain physiological characteristics of plants were selected. Most positive effect occurs in red and blue spectral areas. However full maturing of fruits requires also influence of UV and IR of areas of radiation. Besides, for optically dense leaves, leaves of the lower tiers and dense crops of plants an important role is played by the green area of radiation.

The generalized diagram of optical-electronic system of lighting of plants (OES LP) consisting of a LED source, control box, the personal computer, the sensor of monitoring of radiation and a video camera (optionally) was developed.

The principle of operation of OES LP consists in object lighting by a LED source with a summary range of different wavelengths so that the radiation is as close as possible to spectral sensitivity of a plant. For calibration of lighting part of the system a control box is used. This control box is directly connected to the personal computer.

The control of proposed light source is exercised not only on brightness, but also on spectral content. That allows us to configure mentioned source for different types of cultural plants.

Photodiode sensors can be used for monitoring of radiation parameters of the source. The camera is an element of the form and quality monitoring of plant "organs" for determination of response to various spectral contents of radiation when carrying out the pilot studies.

The three-dimensional model and construction of multielement radiation source on the basis of LEDs is developed. 5 types of LEDs of the different spectral ranges (from long-wave UV to the neighbor IR) were selected as element basis.

Thus, the novelty of the proposed solution consists in a technique of obtaining optimal spectral content of radiation for additional lighting of cultural plants for stimulation of their growth and maturing of fruits.

10124-55, Session PWed

Aerosol and cloud vertical structure in New York City: micro-pulse lidar measurements and validation

Ahmed Hassebo, Sameh Ahmed, The City College of New York (United States); Yasser Y. Hassebo, The City Univ. of New York (United States)

Clouds are playing an important role to regulate and stabilize the hydrological circulation of the earth. Vertical structure of aerosol and cloud in the atmosphere, e.g. amounts of water and ice, cloud thickness and layers, cloud heights, etc., is a critical element for understanding the Earth's climate, the vertical distributions of latent heat release, ocean color investigations, and satellite data corrections. Micro pulse Lidar (MPL) is an eye-safe elastic backscatter Lidar, developed at NASA, deployed at a number of locations worldwide for autonomous aerosol and cloud monitoring that required for atmospheric and climate change investigations. In this paper, we report on the measurements of aerosol and cloud vertical structure in New York City (NYC) using the first polarization MPL located at the City University of New York. MPL operation, setup, data collection and correction will be introduced. Preliminary results and comparison analysis between 2015 and 2016 of cloud vertical structure and the Planetary Boundary Layer (PBL) above NYC will be discussed. An investigation analysis of the impact of rush hour pollution on the level of PBL depth in NYC will be introduced using the MPL temporal measurements. Applications of the MPL tow-polarization channels will be investigated. Potential future studies and collaborations in protecting NYC against environmental disasters by employing more devices along with MPL real-time data will be emphasized. For pedagogical purposes, a lab module was developed to be implemented in the newly developed track in Earth System Science and Environmental Engineering (ESE), more details will be presented.

10124-56, Session PWed

The quality study of recycled glass phosphor waste for LED

Chun-Chin Tsai, Far East Univ. (Taiwan); Guan-Hao Chen, National Univ. of Kaohsiung (Taiwan); Cheng-Feng Yue, Hau-Cen Yen, Far East Univ. (Taiwan); Wood-Hi Cheng, National Chung Hsing Univ. (Taiwan)

To study the feasibility and quality of recycled glass phosphor waste for LED packaging, the experiments were conducted to compare optical characteristics between fresh color conversion layer and that made of recycled waste. The fresh color conversion layer was fabricated through the first sintering mixture of Y.A.G. powders [yellow phosphor ($Y_3Al_5O_{12}:Ce^{3+}$) and green one ($Lu_3Al_5O_{12}:Ce^{3+}$)]. Those recycled waste glass phosphor was secondarily re-melten to form Secondary Melten Glass Phosphor (S.M.G.P.). The experiments on such low melting temperature glass results showed that transmission rates of first-sintered glass phosphor are 9% ~ 14% higher values than those of S.M.G.P., corresponding to 1.25% greater average bubble size and 36% more bubble coverage area for S.M.G.P. However, S.M.G.P. exhibited 9%~14% higher reflectance no matter yellow or green type phosphor. In the recent years, high power LED modules and laser projectors require higher thermal stability by using glass phosphor materials for light mixing. Nevertheless, phosphor and related materials are too expensive to expand their markets. It seems a right trend and research goal that recycling waste of such high thermal stability and quality materials could be the preferable one of feasible cost-down solutions, after feasibility evaluation, if low cost recycling manufacture process can be also demonstrated. This technical approach could bring out brighter future for solid lighting and light source module industries.

10124-57, Session PWed

512x512 array of dual-color InAs/GaSb superlattice light-emitting diodes

Russell J. Ricker, Sydney Provence, Lee M. Murray, John P. Prineas, Thomas F. Boggess, Andrew I. Hudson, Dennis Norton, Jonathon T. Olesberg, The Univ. of Iowa (United States)

InAs/GaSb superlattice light-emitting diodes are a promising technology for progressing the state-of-the art in infrared optoelectronics applications. By targeting a specific band of interest, they are able to achieve apparent temperatures greater than that of conventional resistor arrays and settling times on the order of nanoseconds. We report the fabrication of a dual-color infrared InAs/GaSb superlattice light-emitting diode array for operation in the mid-wave infrared. The two colors are independently operable and occupy the same pixel space. The peaks occur at 3.9?m and 4.9?m, straddling the CO2 absorption band. Using photolithography and wet etching, a 512x512 array of 48?m-pitch pixels were fabricated and hybridized to a silicon read-in integrated circuit. Test arrays with an 8x8 grid of pixels tested at 77K demonstrated greater than 2 W/cm2·sr for the 4.9?m emitter and greater than 5W/cm2·sr for the 3.9?m emitter; the lower radiance in the long-wave emitter is due to a small active region volume left after fabrication. These respectively correspond to apparent temperatures greater than 1400K and 2000K in the 3-5?m band.

10124-58, Session PWed

Validation of Thermal Effects of LED Package by Using Elmer Finite Element Simulation Method

Siang Leng Lai, Vithyacharan Retnasamy, Univ. Malaysia Perlis (Malaysia); Mukhzeer Mohamad Shahimin, National Defence Univ. of Malaysia (Malaysia); Zaliman Sauli, Steven Taniselass, Muhamad Hafiz Ab Aziz, Univ. Malaysia Perlis (Malaysia); Rajendaran Vairavan, Univ Malaysia Perlis (Malaysia); Supap Kirtsaeng, Faculty of Science, Silpakorn University (Thailand)

The characteristics of LED such as high Lumens output, low energy consumption, environment friendly and less maintenance have enabled it become a robust lighting source for the next generation. Currently, the overall performance of the LED package is critically affected by the heat attribution. Presently, most of the thermal analysis study on LED package was conducted using commercial licensed software. In this study, open source software –Elmer FEM has been utilized to study the thermal analysis of the LED package. In order to perform a complete simulation study, both Salome software and Paraview software were introduced as Pre and Post processor. The thermal effect of the LED package was demonstrated by this software. The results have been validated with commercial licensed software.

10124-59, Session PWed

A Comparative Study of Thermal Performance on Commercialised LED Bulb on the Luminaire Geometry

Siang Leng Lai, Vithyacharan Retnasamy, Univ. Malaysia Perlis (Malaysia); Mukhzeer Mohamad Shahimin, National Defence Univ. of Malaysia (Malaysia); Zaliman Sauli, Steven Taniselass, Muhamad Hafiz Ab Aziz, Rajendaran Vairavan, Univ. Malaysia Perlis (Malaysia); Supap Kirtsaeng, Faculty of Science, Silpakorn University (Thailand)

LED promising for energy saving and becomes popular in many applications. The LED lighting bulb is dominating the over the conventional lighting source. The demand of the high Lumens output on commercialised LED bulb has resulted in the increases of operating power and generation of heat. The heat generated has affected the overall performance of the LED bulb. Several commercialised LED bulbs were explored in this study. A study on the thermal performance of several available commercialised LED bulbs was done by using Elmer finite element simulation method. The variation approach was limited to input power and the heat performance was compared. The result gives a comparison on the variation of the model and the heat distribution.

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10125-1, Session 1

Sensing fiber chirality in confined nematics: Chiraogyral effect *(Keynote Presentation)*

Slobodan ?umer, Simon ?opar, Urban Mur, Univ. of Ljubljana (Slovenia); Miha Ravnik, Univ. of Ljubljana (Slovenia) and Jo?ef Stefan Institute (Slovenia); Maria Helena Godinho, CENIMAT-Ctr. de Investigacao em Materials (Portugal); Pawel Pieranski, Univ. Paris-Sud 11 (France)

Microfibers with unidirectional planar surface anchoring along the fiber axis can in a nematic field perpendicular to the fiber stabilize ring defects encircling fibers. The detailed structures of ring disclinations depend on nematic elastic constants and on the confinement. Cellulose fibers often exhibit helically winding of the planar anchoring direction along their axes that is directly reflected in the tilt of the disclination rings. This chirogyral effect we first recognized in nematic drops decorating such fibers. Here we analyze the effect and its possible sensoric application on fibers with helically winding anchoring that are confined to a homeotropic nematic cell.

10125-2, Session 1

Nanoparticle micro-assembly via phase transition dynamics *(Invited Paper)*

Linda S. Hirst, Univ. of California, Merced (United States)

Liquid crystal (LC) phase transition dynamics can be used as a powerful tool to control the assembly of dispersed nanoparticles. By tailoring mesogenic ligands on the particle surface it is possible to both enhance and tune particle dispersion in a liquid crystal phase and to create liquid crystal nano-composites. Soft nano-composites have recently risen to prominence for their potential uses in a variety of industrial applications, i.e. photovoltaics, photonic materials, and the liquid crystal laser. Liquid crystal materials can be designed to include quantum dots, metallic and magnetic particles and we present some recent developments in our lab using the isotropic to nematic phase transition as a template for particle organization and assembly. We present details on the formation process of nanoparticle micro-capsules and other nano composite film geometries using mesogen-functionalized quantum dots and gold particles and discuss their potential applications.

10125-3, Session 1

Topological defects in liquid crystals and molecular self-assembly. *(Invited Paper)*

Nicholas L. Abbott, Univ. of Wisconsin-Madison (United States)

Topological defects in liquid crystals (LCs) have been widely used to organize colloidal dispersions and template polymerizations, leading to a range of elastomers and gels with complex mechanical and optical properties. However, little is understood about molecular-level assembly processes within defects. This presentation will describe an experimental study that reveals that nanoscopic environments defined by LC topological defects can selectively trigger processes of molecular self-assembly. By using fluorescence microscopy, cryogenic transmission electron microscopy and super-resolution optical microscopy, key signatures of molecular self-assembly of amphiphilic molecules in topological defects are observed - including cooperativity, reversibility, and controlled growth of the molecular assemblies. By using polymerizable amphiphiles, we also demonstrate preservation of molecular assemblies templated by defects, including nanoscopic "o-rings" synthesized from "Saturn-ring" disclinations. Our results reveal that topological defects in LCs are a versatile class of three-dimensional, dynamic and reconfigurable templates that can direct processes of molecular self-assembly in a manner that is strongly analogous to other classes of macromolecular templates (e.g., polymer—surfactant complexes). Opportunities for the design of exquisitely responsive soft materials will be discussed using bacterial endotoxin as an example.

10125-4, Session 1

The twist-bend nematic phase: structure property relationships and applications *(Invited Paper)*

Corrie Imrie, Univ. of Aberdeen (United Kingdom)

Liquid crystal dimers consist of molecules containing two mesogenic units linked by a flexible spacer and have been a rich source for the discovery of new types of mesophases.[1] Most recently, a nematic-nematic transition was reported for odd-members of the ?,?-bis-4-(4'-cyanobiphenyl)alkanes.[2,3] Cestari et al. assigned the lower temperature nematic as a twist-bend nematic phase, NTB.[2] This was later confirmed in studies based on freeze fracture transmission electron microscopy.[4,5] In the NTB phase, the achiral molecules form a helix and the director is titled with respect to the helical axis. The induced twist may be either left or right handed and equal amounts of both types of helix are expected. To date, the Ntb phase has been observed for relatively few materials. Given this limited data set, the development of the empirical relationships linking molecular structure to the observation of this exciting new phase is very much at an embryonic stage. Here we present a range of new liquid crystal dimers which exhibit the NTB phase and discuss structure-property relationships. We will also consider the application potential of these types of liquid crystals.[6]

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10125-5, Session 1

Reconfigurable topological defect arrays in nematic liquid crystals *(Invited Paper)*

Venkata Subba Rao Jampani, Univ. du Luxembourg (Luxembourg); Yuji Sasaki, Hokkaido Univ. (Japan); Khoa V. Le, Fumito Araoka, RIKEN (Japan); Hiroshi Orihara, Hokkaido Univ. (Japan)

The broken orientational order in nematic liquid crystals (NLC) results in topological defects of different strength. The defects play crucial roles in many application aspects such as colloidal assembly, molecular self-assembly, sensors, and optical vortex generation. The conventional production of a large array of stable defects in NLCs demands pre-patterned surfaces which are usually achieved by lithography techniques. In this talk, we will present an interesting NLC system which is doped with an ionic impurity and is confined by a fluorinated surfaces without having any surface modifications. By applying an AC electric field, we found that the reorientation of the nematic director spontaneously leads to a large-scale

formation of two-dimensional array of umbilical defects. This method allows us to have reconfigurability of defect arrays by laser irradiation and the lattice size can be tuned by changing either the cell thickness or the applied field strength. We are aiming to apply the system for diffractive microlens arrays, optical vortex generation, and sensor applications.

10125-6, Session 2

Femtoseconds-picoseconds nonlinear optics with liquid crystals *(Invited Paper)*

Iam-Choon Khoo, Chun-Wei Chen, Tsung-Jui Ho, The Pennsylvania State Univ. (United States)

Liquid crystals in their ordered phases (nematic, cholesteric including blue-phase) possess extremely large optical nonlinearities - ultrafast individual molecular nonlinearities that response in the sub-picoseconds time scale and collective crystalline optical nonlinearities that response in milliseconds –nanoseconds [1-3]. We will discuss the underlying theory and recent experimental observations of nonlinear self-action ultrafast (femtoseconds – picosecond) laser pulse compression [4,5] and pulse width modulation processes with cholesteric liquid crystals (CLC). The underlying mechanisms are cholesteric photonic crystal band-edge dispersion acting in concert with the intensity dependent nonlinear self-phase modulation arising from the index change. Since CLC can be fabricated to yield photonic band-edge wavelength location throughout the visible to near IR regime, the aforementioned pulse width modulation processes clearly indicate the feasibility of developing compact and highly reconfigurable pulse modulation devices capable of large dynamic temporal- and spectral- range of operation. References: (1) Physics Reports 471, 221-267 (2009); (2) Progress in Quantum Electronics, Volume 38, Issue 2, Pages 77–117 (2014); (3) Progress In Electromagnetics Research 147 (2014); (4) Optics Letters 38, pp 5040 – 5042 (2013); (5) Optics Express, Vol. 24, Issue 10, pp. 10458-10465 (2016).

10125-7, Session 2

Microlasers made of liquid crystals and biological materials *(Invited Paper)*

Matja? Humar, Jo?ef Stefan Institute (Slovenia) and Harvard Medical School (United States) and Univ. of Ljubljana (Slovenia); Seok-Hyun Yun, Wellman Ctr. for Photomedicine (United States); Igor Mu?evi?, Jo?ef Stefan Institute (Slovenia) and Univ. of Ljubljana (Slovenia)

Most photonic components are traditionally made out of hard materials by top-down methods. Alternatively, soft photonic devices offer a range of advantages, such as self-assembly, adaptability, tunability and self-healing. Here we present microlasers made of a variety of soft materials. Two laser designs were explored: whispering-gallery mode optical cavity and self-assembled onion-like layered structure in a droplet making a spherical Bragg cavity. Nematic or cholesteric liquid-crystal droplets doped with a fluorescent dye were used for this purpose. Natural liquid crystals were employed to make biocompatible lasers that could be implanted into human body. The liquid crystal lasers show high tunability and can be used as temperature or chemical sensors. Lasers completely embedded within single live cells have also been demonstrated. The lasers can be used as very sensitive sensors, enabling us to better understand cellular processes. For example, we measured the change in the refractive index which is directly related to the concentration of chemical constituents within the cells. Further, lasers were used for cell tagging. Each laser within a cell emits light with a slightly different fingerprint, which can be easily detected and used as a bar-code to tag the cell, providing the ability the study cell migration including cancer metastasis. Further, by using a micro pipette, we injected a tiny drop of oil containing fluorescent dye into a cell. By analyzing the light emitted by a droplet laser, we can measure that deformation and calculate the tiny forces acting within a cell. Finally, lasers completely made out of live matter have been demonstrated in adipocytes.

10125-8, Session 2

Cellulose-based liquid crystal hydrogels and aerogels *(Invited Paper)*

Ivan I. Smalyukh, Univ. of Colorado Boulder (United States)

Using bacteria-derived cellulose, we obtain lyotropic nematic and cholesteric liquid crystals that are then transformed into hydrogels and aerogels that preserve liquid crystalline organization of the cellulose nano crystals and nanowires. We demonstrate how these gels can serve as a basis for the design and assembly of novel composite materials with plasmonic, luminescent, and other properties, as well as how nematogels that comprise a matrix in a form of a gel of cellulose nanoparticles and thermotropic liquid crystals can be switched on the time scales of about hundred microseconds. We discuss how cellulose-based liquid crystal composites can enable a host of new applications, such as privacy windows.

10125-9, Session 2

Wide-band tunable photonic bandgap device and laser in dye-doped liquid crystal refilled cholesteric liquid crystal polymer template system *(Invited Paper)*

Jia-De Lin, Hong-Lin Lin, Hsin-Yu Lin, Guan-Jhong Wei, Chia-Rong Lee, National Cheng Kung Univ. (Taiwan)

This work develops wide-band tunable photonic bandgap (PBG) devices and lasers based on dye-doped liquid crystal (DDLC) refilled gradient-pitched enantiomorphic cholesteric liquid crystal (CLC) polymer template samples. The PBG of the device has a high reflectivity (> 50%) and spatial tunability over the entire visible region. After refilling the template with DDLC, a tunable laser can lase from the blue to the red regions (483.18 nm to 633.73 nm). In comparison with the refilled gradient-pitched single-handed template device, the enantiomorphic one is highly reflective and provides an efficiently simultaneous resonance for both right- and left-circular fluorescence, which can cause a lower energy threshold for the lasing emission in the visible region. The refilled enantiomorphic template laser possesses many advantages, such as high stability and reliability, reliable tunability in both PBG and lasing wavelength within visible region, simultaneously supporting two oppositely-handed circular lasing emissions, lower lasing threshold comparing to that of single-handed template laser.

10125-10, Session 3

Dynamic and reversible tuning of nanoparticle assemblies in the topological defects of liquid crystals *(Invited Paper)*

Shu Yang, Univ. of Pennsylvania (United States)

Assemblies of functional nanoparticles (e.g. metallic and quantum dots) will lead to unique optical properties for potential applications in sensing, imaging, and light modulation. However, it remains challenging to dynamically and reversibly switch the assembly and disassembly of nanoparticles for a large shift of optical responses given a specific stimulus. Liquid crystals (LCs), owing to their anisotropy in molecular ordering, offer a new route to direct nanoparticle assemblies, and thus, optical responses. Here, I will show how we have brought together these two materials by patterning surface topographies, topologies, and chemistries to guide the molecular alignment of LCs on surfaces and interfaces. In turn, these surface cues create and control topological defects that allow trapping, transportation, and actuation of nanoparticles. Specifically, we show dynamic tuning the (dis)assembly of gold nanorods (AuNRs) in topological defects of nematic LCs confined within micropillar arrays near the phase transition temperature. Due to their anisotropic shape, AuNRs favor side-

to-side packing in the isotropic phase to maximize translational entropy at the loss of rotational entropy but switch to end-to-end assembly in LC defect core when cooled to the nematic phase, which is energetically more favorable to maximize their occupancy of the disclination line. In turn, the localized surface plasmon resonance peak wavelength can be reversibly shifted more than 100 nm. The interplay of LC defect core at nanoscale and surface cues at the microscale to create topological defects as demonstrated in our systems suggest a new route in the quest for active and highly sensitive optical devices.

10125-11, Session 3

Do small molecules assemble at topological defects of a liquid crystal? *(Invited Paper)*

Jun-ichi Fukuda, National Institute of Advanced Industrial Science and Technology (Japan)

Topological defects of a liquid crystal are known to trap macroscopic objects such as colloidal particles and polymer molecules, because high free energy density at the defect core can be relaxed when objects other than the host liquid crystal replaces the liquid crystal volume of the defect core with high free energy density. Such a mechanism has been exploited for the stabilization of cholesteric blue phases by guest components such as a polymer matrix and nanoparticles. It has also been demonstrated that macroscopic objects can be manipulated by topological defects. However, it is not yet clear whether the same mechanism can be applied to small molecules that do not self-assemble in the bulk of the liquid crystal, because, in contrast to macroscopic objects, entropy gives rise to a uniform distribution such small molecules unless phase separation or self assembly is driven by enthalpy. Here we show theoretically that the trapping power of topological defects can be strong enough to give rise to a non-uniform distribution of such small molecules. We show this by evaluating the mixing entropy of a binary system composed of liquid crystals and guest molecules using the Flory-Huggins theory, and the free energy density of the liquid crystal at the defect core using the Landau-de Gennes theory.

Therefore, tailored arrays of topological defects could be utilized as a scaffold for the assembly of small molecules providing novel structures and functions, and we hope that our theoretical work will motivate experimental studies towards the design of novel functional materials making use of topological defects.

10125-12, Session 3

Vertical slippery interfaces: lubrication of intra- and inter-helix C-director rotation motions *(Invited Paper)*

Jun Yamamoto, Waki Sakatsuji, Kyoto Univ. (Japan) and Japan Science and Technology Agency (Japan); Isa Nishiyama, Dainippon Ink and Chemicals, Inc. (Japan) and Japan Science and Technology Agency (Japan)

Anchoring effects on the polymer films in the liquid crystal (LC) display devices plays key role to create the restoring force to the black state. However, the chiral materials with spontaneous helix, such as deformed helix mode in SmC* (DH-FLC) or the polymer stabilized blue phase (PSChBP), can recover black state by rewinding motion of the helix itself. We have invented the principle and design of slippery interfaces, which has zero anchoring force for attached LC molecules on the interfaces, and confirmed the drastic reduction of driving voltage in DH-FLC mode of SmC* (<1 order) keeping the fast switching response (tau~50 micro sec).

We have reported the latteral slippery interfaces consist of the phase separated liquid phases created by tran-cis isomerization of doped azo dye[1]. It is not enough to the complete transmission of the light(I/I0~1) by applying the typical driving voltage (~1.0V/micro m) for current IPS pannels. It is also problem that slippery interface become effective only just below the I-SmC phase transition temperature (TIC-T<20º).

Here, we report new type of the vertical slippery interface realized by the spin coated swollen azo-LC gel films on the glass substrates. Under UV irradiation, trans-cis isomerization of the azo-dye co-polymerized in the azo-LC gel film, induces the vertical slippery intefaces by the disordering effect. Since the co-polymerized azo-dye cannot be dissolved into LC, the disordering effect is complitely localized in the inteface between swollen azo-LC gel and bulk SmC* material. Then the slippery interfaces can be stablized over wide temperature range. We greatly improve the reduction of the driving voltage, I/Io=1, 1.0V/micro m for rather slow change of the driving voltage (tau~1msec 2.5msec pulse), I/I0=0.6, 1.5V/micro m for fast change (tau~50 micro sec, 250 micro sec pulse) by lubrication of intra and inter helix C-director rotation motions.

10125-13, Session 3

Liquid crystalline composites toward organic photovoltaic application *(Invited Paper)*

Yo Shimizu, Lydia Sosa-Vargas, Woong Shin, Yumi Higuchi, National Institute of Advanced Industrial Science and Technology (Japan); Hiromichi Itani, Osaka Univ. (Japan) and National Institute of Advanced Industrial Science and Technology (Japan); Koki Kawano, National Institute of Advanced Industrial Science and Technology (Japan); Quang Duy Dao, Akihiko Fujii, Masanori Ozaki, Osaka Univ. (Japan)

Liquid crystalline semiconductor is an interesting category of organic electronic materials and also has been extensively studied in terms of "Printed Electronics". For the wider diversity in research toward new applications, one can consider how to use a combination of miscibility and phase separation in liquid crystals. Here we report discotic liquid crystals in making a composite of which structural order is controlled in nano-scale toward photovoltaic applications.

Discotic columnar LCs were studied on their resultant molecular order and carrier transport properties. Liquid crystals of phthalocyanine and its analogues which exhibit columnar mesomorphism with high carrier mobility (10-1 cm2/Vs) were examined with making binary phase diagrams and the correlation to carrier transport properties by TOF measurements was discussed. The shape-analogues in chemical structure shows a good miscibility even for the different lattice-type of columnar arrangement and the carrier mobility is mostly decrease except for a case of combination with a metal-free and the metal complex. For the mixtures with non-mesogenic C60 derivatives, one sees a phase-separated structure due to its immiscibility, though the columnar order is remained in a range of component ratio.Especially, in a range of the ratio, it was observed the phase separated C60 derivatives are fused into the matrix of columnar bundles, indicating C60 derivatives could be diffused in columnar arrays in molecular level.

10125-14, Session 4

In situ creation of reactive polymer nanoparticles and resulting polymer layers formed at the interfaces of liquid crystals *(Invited Paper)*

Shin-Woong Kang, Sudarshan Kundu, Chonbuk National Univ. (Korea, Republic of); Heung-Shik Park, Keun Chan Oh, Jae Jin Lyu, Samsung Display Co., Ltd. (Korea, Republic of)

We report the in situ creation of reactive polymer nanoparticles and resulting polymer networks formed at the interfaces of liquid crystals. It is known that polymerization-induced phase separation proceeds in two distinct regimes depending on the concentration of monomer. For a high monomer concentration, phase separation occurs mainly through the spinodal decomposition process, consequently resulting in interpenetrating polymer networks. For a dilute system, however, the phase separation mainly proceeds and completes in the binodal decomposition regime. The system resembles the aggregation process of colloidal particle. In this case, the reaction kinetics is limited by the reaction between in situ created polymer aggregates and hence the network morphologies are greatly influenced by the diffusion of reactive polymer particles. The thin polymer layers localized at the surface of substrate are inevitably observed and can be comprehended by the interfacial adsorption and further cross-linking reaction of reactive polymer aggregates at the interface. This process provides a direct perception on understanding polymer stabilized liquid crystals accomplished by the interfacial polymer layer.

The detailed study has been performed for an extremely dilute condition (below 0.5 wt%) by employing systematic experimental approaches. Creation and growth of polymer nanoparticles have been measured by particle size analyzer. The interfacial localization of polymer aggregates and resulting interfacial layer formation with a tens of nanometer scale have been exploited at various interfaces such as liquid-solid, liquid-liquid, and liquid-gas interfaces. The resulting interfacial layers have been characterized by using fuorescent confocal microscope and field emission scanning electron microscope. The detailed processes of the polymer stabilized vertically aligned liquid crystals will be discussed in support of the reported study.

10125-15, Session 4

Morphing dynamics in light-triggered liquid-crystal network coatings *(Invited Paper)*

Dirk J. Broer, Technische Univ. Eindhoven (Netherlands)

Polymers that can change shape or surface topography in response to a trigger have a wide application potential varying from micro-robotics to avionics. Preferably this morphing proceeds fast and reversibly. We developed new morphing principles based on in-situ photopolymerized liquid crystal networks and on hybrid low molecular weight liquid crystals and liquid crystal networks. Commonly the triggers are temperature, light, pH or the presence of chemicals or other moisture. In the lecture we will focus on UV actuation and demonstrate that by accurate positioning of molecules over all three dimensions of a thin film or coating, the deformation figures can be pre-engineered. They can vary from simple gratings to very complex such as fingerprints that can be switched between off (flat surface) and on (corrugated surface) by light. The underlying principles are based on photo-induced changes in the degree of order of liquid crystal polymer networks and the accompanying changes in density by the formation of free volume. The surfaces can be switched with frequencies of the order of 0.1 Hz. In the lecture we will discuss several methods to fabricate the responsive layers as well as some of the most eye-catching properties. Also the mechanism of free volume generation will be addressed in terms of molecular dynamics and resonance.

10125-16, Session 4

Photoresponsive smart surface of LC azo-dendrimer: Photomanipulation of topological structures and real-time imaging at a nano-scale *(Invited Paper)*

Fumito Araoka, RIKEN (Japan); Alexey Eremin, Otto-von-Guericke Univ. Magdeburg (Germany); Satoshi Aya, RIKEN (Japan); Atsuki Ito, Tokyo Institute of Technology (Japan); Hajnalka Nádasi, Nerea Sebastian, Otto-von-Guericke Univ. Magdeburg (Germany); Ken Ishikawa, Tokyo Institute of Technology (Japan); Osamu Haba, Yamagata Univ. (Japan); Ralf Stannarius, Otto-von-Guericke-Univ. Magdeburg (Germany); Koichiro Yonetake, Yamagata Univ. (Japan); Hideo Takezoe, Toyota Physical and Chemical Research Institute (Japan)

Photo-manipulation of liquid crystals (LCs) has been intensively studied not only due to the advantage of its contact-free alignment over the conventional rubbing method but also the possibility of novel photo-responsive smart materials. For instance, quite recently, biomimetic motion of a photo-active LC elastomer has been demonstrated, which may lead to new principles for photo-mechanical micro devices.

In this presentation, we demonstrate a photo-responsive smart surface composed of liquid crystalline dendrimers having a photoresponsive azobenzene moiety, at which photo-isomerization may lead to reversible switching between homeotropic and planar anchoring conditions, when exposed to UV/VIS light. Such drastic change in the surface condition brings about a variety of intriguing features in LC systems, not only the bulk orientational change but also photo-mechanical translational and rotational motions of micro-particles, and photo-induced transformation of the interior topological structures of nematic, cholesteric and smectic droplets.

In spite of such phenomenological observations, the detailed conditions of such photo-responsive interfaces have not yet been well understood. Here we also demonstrate the detailed study on such photo-responsive surfaces including a real-time filming of wetting/de-wetting processes at a nano-scale by means of an unconventional video-rate atomic force microscopy (v-AFM). The polar anchoring energy at the interface upon photo-isomerization under illumination of UV and/or VIS lights was discussed experimentally based on Glazing Incidence X-ray Diffraction, Polarization Microscopy, Second Harmonic Generation, and Attenuated Total Reflection Infrared Spectroscopy, and theoretically based on the simple Rapini-Papoular model.

10125-18, Session 5

Polymer/LC gratings

Luciano De Sio, BEAM Engineering For Advanced Measurements Co. (United States); Cesare P. Umeton, Univ. della Calabria (Italy); Nelson V. Tabiryan, BEAM Engineering For Advanced Measurements Co. (United States); Timothy J. Bunning, Air Force Research Lab. (United States)

We present and discuss a simple and effective study devoted to characterize the NLC alignment inside a POLICRYPS structure. The characterization is performed by continuously varying the distance (periodicity) between the polymeric channels through a chirped POLICRYPS structure. In order to study the NLC orientation between the polymeric walls, we have inspected the chirped POLICRYPS structure with a Mueller Matrix Spectroscopic Polarimeter. It turns out that for large and average periodicity, there is an incomplete phase separation and the NLC does not appear well organized within the polymeric channels. For short periodicity, there is a complete phase separation with a noticeable indication that the orientation of the NLC molecular director inside the structure is perpendicular to its polymeric slices.

10125-19, Session 5

Switchable-focus lenticular microlens array (LMA)

Xiahui Wang, Hongwen Ren, Chonbuk National Univ. (Korea, Republic of)

A switchable-focus lenticular microlens array (LMA) is an essential component for switchable 2D/3D displays because it offers the highest transmittance. For 2D display, the LMA has no optical power and it functions as an optical flat plate. To achieve 3D display, each microlens in the array should have optical power. To prepare a switchable-focus LMA, various approaches have been demonstrated. Each approach has its own strengths and limitations. In this report, two approaches for preparing a LMA are introduced. One is based on polymer network liquid crystal (PNLC) and the other is based on electrically charged PVC/DBP gel. When the PNLC LMA integrates with a LC polarized rotator, a switchable focus can be obtained by driving the LC polarized rotator. The advantages of this focus switch is the low driving voltage and fast response time. As a comparison, the PVC/DBP based LMA is the newly developed device. Its focal length can be tuned from infinity to a certain distance by a DC voltage. It owns the unique properties of compact structure and high optical performance. The operation mechanisms of both LMAs are introduced and their performances are evaluated. Owing to their unique performances, both LMAs are desirable in switchable 2D/3D displays.

10125-20, Session 5

New photoresponsible polymers based on the polymerisable azo-diphenyldiacetylene (AZ-DPDA) liquid crystalline monomers for rewritable holograms *(Invited Paper)*

Jinsoo Kim, Jae-Won Ka, Yun Ho Kim, Korea Research Institute of Chemical Technology (Korea, Republic of); Yeong-Joon Kim, Chungnam National Univ. (Korea, Republic of); Young Beom Seo, Korea Research Institute of Chemical Technology (Korea, Republic of) and Chungnam National Univ. (Korea, Republic of)

The development of high performance and large area photoresponsive materials for hologram have been one of the great challenges in order to realize holographic 3D display technology which needs no special eyewear. Desirable hologram materials should provide the high diffraction efficiency, fast response, high resolution, stable and reversible storage, low-energy consuming in the recording and reading processes as well as easy mass production. Azobenzene-containing polymers has been recognized as one of the promising candidate materials for holography because they can modulate effectively due to the photosensitivity and reversibility of azo moieties. In addition, polymer systems have several advantages such as simple fabrication, flexibility, thermal stability, and large scale production. It has been reported that highly birefringent azotolan-containing liquid crystalline polymer (LCP) film can induce a large change in refractive index upon exposure to actinic light. Analogously, we prepared new photochromic polymers based on the polymerisable liquid crystalline acrylate monomers (RMs) containing azo and highly birefringent diphenyldiacetylen (DPDA) mesogenic units connected directly. Evaluation of new polymers for rewritable hologram media will be discussed.

10125-21, Session 5

Determination of the two-photon absorption cross-section of magnetite and manganese ferrite nanoparticles in ferrofluids and thin films

Daniel Espinosa, Eduardo S. Gonçalves, Antonio M. Figueiredo Neto, Univ. de São Paulo (Brazil)

Nonlinear optical properties of colloids have technological appeal, since nanoparticles with nonlinear optical properties can be combined with the fluidity of liquid carriers, in the emerging area of Optofluidics. Ferrofluids, especially, can be used in magnetically-controllable applications or in optical limiting devices, where nonlinear absorption is a key characteristic. Besides two-photon absorption, some phenomena are present in experimental studies in optical nonlinearities of colloids: the particles can absorb light and heat the liquid around it, giving rise to a temperature and a subsequent refractive index gradient, what originates a thermo-optical self-focusing; also, the temperature gradient can drive the particles inward or outward the illuminated region, what changes the refractive index and the absorption coefficient of the material. In this work, the z-scan technique is performed in ferrofluids and thin films made from ferrofluids to measure the two-photon absorption coefficient of magnetite and manganese ferrite nanoparticles and to determine their two-photon absorption cross-section (?2PA). To avoid the influence of the cited thermo-optical effects in these measurements, the frequency of the pulsed Gaussian beam (pulse width of 196 fs) is decreased with an electro-optic modulator and a shutter is used to allow the measurement of the nonlinear effects, present at the first pulse illuminating the sample, after a period of 2 seconds without illumination. The z-scan curves with and without using shutter are compared in colloids and thin films. The achieved values of ?2PA at 800 nm are 50 GM and 107 GM, for the magnetite and manganese ferrite nanoparticles, respectively.

10125-26, Session 6

Ultrahigh-resolution phase-only LCOS spatial light modulator *(Invited Paper)*

Grigory Lazarev, Friedemann Gädeke, Jarek Luberek, HOLOEYE Photonics AG (Germany)

We implemented 10 Megapixel liquid crystal on silicon phase-only spatial light modulator (SLM) for the visible and for the shortwave infrared spectral bands. The device provides the spatial resolution exceeding 130 lp/mm. We analyze the electro-optical properties, temporal noises, spatial modulation characteristic, reflectivity and diffraction efficiencies for the implemented devices. We discuss challenges to achieve the high diffraction efficiency and high reflectivity for the devices with very small pixel sizes. We compare the performance of 10 Megapixel SLM and 2 Megapixel SLM in digital holography using simple resolution target patterns.

10125-27, Session 6

The selective reflection of cholesteric liquid crystal *(Invited Paper)*

Huai Yang, Peking Univ. (China)

Researches in self-organizing helical architectures with extraordinary optical performances receive much concern because they play currently a critical role in optical area. Cholesteric liquid crystals undoubtedly represent such fascinating soft materials with Bragg reflection in a "green", efficient and low-cost approach, owing to their inherent self-organized periodic helical structures. Typically, the reflection is selective, which is a consequence of the limitation of bandwidth (within 100 nm) and reflectance (50% at most). This paper provides an overview of novel cholesteric-liquid-crystalline materials in recent developments, which exhibit unique optical bandgaps to break through the polarization-selectivity rule.

10125-28, Session 6

Lateral shearing properties of twisted nematic liquid-crystal cell and its potential application to differential interference contrast imaging *(Invited Paper)*

Toshiaki Nose, Shosei Ishizaka, Keiju Okano, Naoko Fujita, Jun Murata, Hajime Muraguchi, Noriaki Ozaki, Michinori Honma, Ryota Ito, Akita Prefectural Univ. (Japan)

Liquid crystal cell behaves as an optically uniaxial crystal and some lateral shear phenomena occur under a low voltage application, because oblique optical axis distribution state appears. In this work, a pair of twisted nematic liquid crystal (TNLC) cells is introduced to the normal polarization microscope system to attain differential interference contrast (DIC) imaging, which is known as a powerful observation method of weak contrast sample such as a bio cell.

DIC imaging is usually obtained by using a pair of Nomarski prisms, which separates and combines the input image laterally. Although the shear distance, which determines the DIC sensitivity, is fixed in the normal system, it becomes tunable with a fast response speed by using the LC cells. Furthermore, unique lateral shearing properties of the TNLC cell achieve self-compensation of optical retardation, and then we can use the incoherent illumination of normal microscope system for the DIC observation as usual. Here, fundamental lateral shear properties and operational mode for the DIC imaging are investigated.

10125-29, Session 6

Generation of optical vortices with controllable topological charges and polarization patterns

Ching Han Yang, Andy Ying-Guey Fuh, National Cheng Kung Univ. (Taiwan)

We present a simple and flexible method to generate various vectorial vortex beams (VVBs) with a Pancharatnam phase based on the scheme of double reflections from a single liquid crystal spatial light modulator (SLM). In this configuration, VVBs are constructed by the superposition of two orthogonally polarized orbital angular momentum (OAM) eigenstates. To verify the optical properties of the generated beams, Stokes polarimetry is developed to measure the states of polarization (SOP) over the transverse plane, while a Shack–Hartmann wavefront sensor is used to measure the OAM charge of beams. It is shown that both the simulated and the experimental results are in good qualitative agreement. In addition, polarization patterns and OAM charges of generated beams can be controlled independently using the proposed method.

10125-22, Session 7

Design of temperature-independent zero-birefringence pressure sensitive adhesives *(Invited Paper)*

Kaoru Kosaka, Houran Shafiee, Keio Univ. (Japan); Hiroyuki Ogawa, Sumihisa Oda, Saiden Chemical Industry Co., Ltd. (Japan); Akihiro Tagaya, Yasuhiro Koike, Keio Univ. (Japan)

Liquid crystal displays (LCDs) are composed of two glass substrates, two polarizers and some optical films. These components are laminated by pressure sensitive adhesives (PSAs). When a polarizer shrinks by humidity or the heat from a backlight of LCDs, stress appears and deforms PSAs. PSAs tend to exhibit birefringence due to applied stress and temperature change, which causes light leakage degrading image quality of LCDs. PSAs are consisted of main chain polymers and cross-linkers. To evaluate birefringence of PSAs at room temperature is difficult because PSAs easily plastically deform at the temperature. The purpose of this article is to design temperature-independent zero-birefringence PSAs (TIZBPSAs) exhibiting almost no birefringence even during stress-induced deformation over a wide temperature range. Butyl acrylate (BA) and phenoxyethyl acrylate (PHEA) were selected as the monomers of main chain polymers and an isocyanate-type cross-linker was added. Trilaminar films were prepared in which PSAs were sandwiched between two supporting films. We successfully evaluated birefringence and temperature dependence of birefringence of PSAs for the first time by using temperature-independent zero-birefringence polymers (TIZBPs) as the supporting films. TIZBPs, designed in our group, show almost no orientational birefringence even when the polymer main chain is in an oriented state and almost no temperature dependence of orientational birefringence over a wide temperature range. We have proposed a novel method to design PSAs having desirable the birefringence properties by determining the contributions of BA, PHEA and the cross-linker to birefringence and temperature dependence of PSAs quantitatively. Furthermore, we have designed TIZBPSAs by the proposed method.

10125-23, Session 7

Control of double refraction in anisotropic metamaterials *(Invited Paper)*

Miha Ravnik, Univ. of Ljubljana (Slovenia) and Jo?ef Stefan Institute (Slovenia); Anja Bregar, Jure Aplinc, Univ. of Ljubljana (Slovenia)

Optical metamaterials control the flow-of-light via their internal structure, giving rise to novel optical phenomena like super lensing and negative refraction. Here, we show the study of the control of refraction by optical anisotropy in liquid crystal-like metamaterials. Birefringence is varied showing that selected combinations of dielectric permittivity and permeability, in combination with the control over the optical axis, can lead to a broad control over both the light wave vectors as well as the Poynting vector. Methodologically, we use a combination of analytical approaches and Finite Difference Time Domain numerical calculations. More broadly, this work is an attempt towards realising liquid crystal-like performing matamaterials.

10125-25, Session 7

Smart windows based on cholesteric liquid crystals

Hitesh Khandelwal, Michael G. Debije, Albert P. H. J. Schenning, Technische Univ. Eindhoven (Netherlands)

With increase in global warming, use of active cooling and heating devices are continuously increasing to maintain interior temperature of built environment, greenhouses and cars. To reduce the consumption of tremendous amount of energy on cooling and heating devices we need an improved control of transparent features (i.e. windows). In this respect, smart window which is capable for reflecting solar infrared energy without interfering with the visible light would be very attractive.

Most of the technologies developed so far are to control the visible light. These technologies block visual contact to the outside world which cause negative effects on human health. An appealing method to selectively control infrared transmission is via utilizing the reflection properties of cholesteric liquid crystals. In our research, we have fabricated a smart window which is capable of reflecting different amount of solar infrared energy depending on the specific climate conditions. The reflection bandwidth can be tuned from 120 nm to 1100 nm in the infrared region without interfering with the visible solar radiations. Calculations reveal that between 8% and 45% of incident solar infrared light can be reflected with a single cell. Simulation studies predicted that more than 12% of the energy spent on heating, cooling and lighting in the built environment can be saved by using the fabricated smart window compared to standard double glazing window.

10125-30, Session 8

Cholesteric microlenses and micromirrors *(Invited Paper)*

Michel Mitov, Gonzague Agez, Chloé Bayon, Ctr. d'Elaboration de Matériaux et d'Etudes Structurales (France)

In cholesteric oligomeric films, we investigate the light transmission properties of the polygonal texture in 3D by using a spectrometer equipped with a confocal microscope [1]. It is found that the focusing properties are wavelength tunable. The light intensity and the focal length depend on the lens diameter and on the annealing time [2]. The helical organization of the layer is at the origin of the focusing and not its surface shape like in conventional microlenses. A concept of light manipulation using chirality is demonstrated, which concerns color sensitive devices like high efficiency CCD image sensors, laser trapping or wavelength–tunable directional sources in soft-matter circuits [3]. Then we investigate the polygonal texture in the cholesteric cuticle of Chrysina gloriosa beetle [4]. We describe its micro-mirror behavior by mapping the reflection properties in visible and NIR spectra. The purpose of this presentation is to provide in detail a comparison between the synthetic and beetle-like micro-mirrors/lenses by a full set of investigations on both systems: optical measurements, structure (SEM, TEM) and numerical simulations (FDTD).

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10125-31, Session 8

Active liquid-crystal deflector and lens with Fresnel structure *(Invited Paper)*

Giichi Shibuya, Shohei Yamano, Hiroyuki Yoshida, Masanori Ozaki, Osaka Univ. (Japan)

A new type of active deflector and lens based on liquid crystal (LC) was developed. We have applied the Fresnel structure to expand the aperture of the lens. Combined structure of multiple interdigitated electrodes and a high-resistivity layer induces a saw-tooth distribution of electrical potential under the planar transparent substrates. The deflection angle of the beam incident normally on the device increased continuously with an increase in the applied voltage. Using the Fresnel structure, a larger maximum deflection angle was achieved compared to the device without the Fresnel structure. Another advantage of the structure is the large aperture when we use that for the lens. We also prepared LC lens samples with a diameter of 13 mm and the lens power was estimated from the obtained interference fringes with the number of over 180 in the full lens aperture. Maximum tilt angle of ±1.3 deg. and lens power of ±4.0 diopter were achieved with the tunable LC devices.

10125-32, Session 8

Recent advances in liquid-crystal fiber-optics and photonics *(Invited Paper)*

Tomasz R. Wolinski, Warsaw Univ. of Technology (Poland)

Over the last twenty years liquid crystals (LCs) have been successfully used to infiltrate fiber-optic (micro) structures including initially hollow-core fibers [1,2] and then microstructured optical fibers [3-7].

Since 2003, there has been an increasing interest in photonic crystal fibers (PCFs) infiltrated with liquid crystals [3]. This combination creates a new class of microstructured fibers known as photonic liquid crystal fibers (PLCFs) [5] in which thermal and electrical tuning possibilities along with unique spectral or polarization properties have been demonstrated [4-7]. PLCFs benefit from a merge of passive PCF host structures with "active" LC guest materials and could be responsible.

The lecture discusses the latest developments in the field of the for diversity of new and uncommon propagation and polarization properties. PLCFs including also nanoparticles-doped LCs. Recently, doping of liquid crystals with nanoparticles has become a common method of improving their optical, magnetic, electrical, and physical properties. Such a combination of nanoparticles-based liquid crystals and photonic crystal fibers can be considered as a next milestone in developing a new class of fiber-based optofluidic systems.

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10125-33, Session 8

Low-voltage binary operation of liquid-crystal Fresnel lens with surface relief structure

Kai-Han Chang, Dong Wang, Liang-Chy Chien, Kent State Univ. (United States)

We demonstrate a liquid crystal Fresnel lens (LCFL) with a surface relief structure which has the binary switching property and the merit of low voltage driving. The surface relief structure is fabricated by photo-polymerization of a polymer-precursor initiated by ultra-violet light onto a solid cylindrical Fresnel lens with desired optical power. A liquid crystal (LC) layer is sandwiched between a pair of polymer Fresnel lens deposited with planar alignment layers with orthogonal rubbing directions. The ordinary refractive index of LC is chose to be close to the refractive index of the polymer. At voltage-off state, when the polarization of light is parallel to the long axis of LC molecules, the refractive index mismatch of liquid crystals and polymer Fresnel lens enables the focusing of LCFL. At voltage-on state, the LCFL is a slab with homogenous refractive index because of the index matching between LC and polymer. With the benefit of twisted nematic structure, the voltage requirement is significantly low (~6V) for LCFL. The low-voltage binary beam shaping of laser and magnifying lens function using LCFL are experimentally demonstrated in this paper.

10125-42, Session 8

Experimental realization and characterization of a F/1.5 geometric-phase lens with high-achromatic efficiency and low aberration

Kathryn J. Hornburg, Jihwan Kim, Michael J. Escuti, North Carolina State Univ. (United States)

Here, we report on the fabrication and properties of a 24.5 mm diameter and 0.45 mm thick lens, manifesting F/1.5 at 633 nm, high efficiency across 450-700 nm, and low aberration. This lens is formed as a thin-film of a photo-aligned liquid crystal polymer network, and is a type of Geometric-Phase Lens (GP Lens), which employs the Pancharatnam-Berry phase.

Geometric-Phase Holograms [1,2] are inhomogeneous optical elements that impose a purely geometric-phase shift. Because the fundamental mechanism for phase control is different than traditional refractive elements, versatile and physically thin lenses, gratings, and other holograms may be created with high efficiency into a single output wave, easy selection of the conjugate wave, and extremely wide bandwidths of operating (e.g., 400-900 nm and 2-5 μm). Recent advances in patterning tools [2-3] and techniques now allow arbitrary phase profiles to be recorded as fixed and switchable liquid crystal films, with large area and high phase slopes.

One element that is particularly interesting is the GP Lens due to their very low thickness, their polarization-dependent focusing, and the potential for low F-numbers in a flat slab. Prior work on GP Lenses in photo-aligned liquid crystals [2,4] and metasurfaces [5] has been limited to larger F/#s (≥F/2.1 or ≥F/7, respectively) or small areas (≤16mm or <5mm, respectively), or both. This talk reports on the largest and fastest GP Lens reported to date.

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10125-34, Session 9

Recent advances in fast-switching liquid-crystal mode based on uniform lying helix (ULH) *(Invited Paper)*

Michael Wittek, Simon Siemianowski, Bernd Fiebranz, Melanie Klasen-Memmer, Merck KGaA (Germany)

Uniform lying Helix (ULH) is one of the most promising new LC modes for fast switching applications with alternative driving schemes such as FSC (field sequential colour). ULH operates via flexoelectric switching, unlike current commercially available liquid crystal modes that operate via dielectric switching. The realisation of mixtures with suitable flexoelectric properties requires unique materials composed of specially designed ´bi-mesogens´ and also the addition of a chiral dopant. Recent advances, updated mixture performance and other challenges such as alignment and driving for this new mode are discussed.

10125-35, Session 9

Optical homogenizing effects in nanoparticle-embedded liquid-crystal devices *(Invited Paper)*

Shunsuke Kobayashi, Yukihide Shiraishi, Hirokazu Furue, Tokyo Univ. of Science (Japan); Kai-Han Chang, Liang-Chy Chien, Kent State Univ. (United States)

Doping of nanoparticles of P?CyD-ZrO2 and Aerosil 812(EVONIK) into ECB and TN LCD cells causes disappearance of laser speckle patters and diffraction patters appearing in the NPs free cells and we got perfect optical appearance in the NP embedded LC cells and at the same time we got a widening of viewing angles in NP embedded LC cells compared to NP free cells with an instrument of ELDEM. These effect are explained through theoretical analysis and computer simulations as to be attributed to optical scattering and de-coherence, where the size of NPs is 50nm less than wave length of Ar laser 400nm, and further decrease of per-tilt angles due to the existence of these NPs.

10125-36, Session 9

Fast in-plane switching of nematic liquid crystals by two-dimensional confinement with virtual walls *(Invited Paper)*

Tae-Hoon Choi, Pusan National Univ. (Korea, Republic of); Jae-Hyeon Woo, Pusan National Univ (Korea, Republic of); Yeongyu Choi, Seung-Won Oh, Tae-Hoon Yoon, Pusan National Univ. (Korea, Republic of)

In-plane switching (IPS) liquid crystal (LC) displays have been widely used in various applications because of their advantageous features, such as wide viewing angle, small color shift, and pressure resistance. However, the response time of an IPS cell is relatively slow because the restoring elastic torque is governed primarily by the twist elastic constant K22, which is generally smaller than the value of the other two elastic constants, namely, the splay elastic constant K11 and the bend elastic constant K33. Fast switching of nematic LCs remains an important technical issue to be solved because the slow response time causes motion blur and deteriorated image quality. In this talk, we introduce a method for achieving a short response time in an IPS cell by two-dimensional confinement of LCs with virtual walls. When an electric field is applied to an IPS cell with zero rubbing angle, virtual walls are built so that the switching speed can be increased several-fold. Furthermore, an IPS cell with zero rubbing angle exhibits reduced color shift and wide-viewing-angle thanks to the multi-domain effect.

10125-37, Session 9

Amorphous blue phase-III polymer scaffold as a sub-millisecond switching electro-optical memory device

Sahil Sandesh Gandhi, Min Su Kim, Kent State Univ. (United States); Jeoung-Yeon Hwang, Kent State University (United States) and Beam Engineering for Advanced Measurements Co. (United States); Liang-Chy Chien, Kent State Univ. (United States)

We present a polymer scaffold that imitates the three-dimensional nanostructure of the amorphous blue phase III (BPIII) of cholesteric liquid crystals (LCs) by forming a reactive mesogen polymer network in the nano-environments created by self-assembled disclinations (topological defects) in BPIII and subsequently washing out the cholesteric LC. This polymer model of BPIII provides the first direct and conclusive morphological observation of the amorphous nature of BPIII, whose structure has only been speculated upon in theory so far. The empty polymer scaffold inherits the achromatic dark state, optical isotropy, and sub-millisecond EO switching characteristics, that is, "EO-memory"of the original BPIII and can transfer them to conventional nematic liquid crystals (LCs) upon refilling the scaffold. We also fabricate scaffolds imitating the cubic blue phase I (BPI) and the isotropic phase to demonstrate the adaptability of our material system to nano-engineer EO-memory scaffolds of various structures. This work will promote renewed experimental exploration of the fundamental properties of BPs in general and BPIII in particular, and open pathways to new materials and device architectures for display and photonic applications.

10125-38, Session 9

Full-color cholesteric liquid crystal reflective films with narrow linewidth

Dan Luo, Yong Li, South Univ. of Science and Technology of China (China)

Recently, cholesteric liquid crystals (CLC) based color reflective films have attracted considerable research interest for developing various applications such as reflective liquid crystal displays. Comparing with pure CLC devices, the CLC film are characterized by features such as flexible, single substrate, simplicity and ease of use. For reflective display, the selectively reflected colors from CLC reflective films are usually highly saturated, which could produce color gamut greater than that of inks, dyes, and pigments [1]. However, the linewidth of CLC reflective film reported is relatively large and around ~90 nm [2]. Decrease of linewidth of CLC reflective films is extremely useful to improve the color purity of the reflected lights [3].

In this paper, we demonstrate a micro-cavity model fabricated by cholesteric liquid crystal and reactive mesogen. The reflective film is fabricated by refilling liquid crystal into the polymer micro-cavity. For green color, the linewidth of CLC reflective film is around 63.6 nm if the refilling liquid crystal possesses large refractive birefringence, which can be largely reduced to around 40.8 nm by 36% if liquid crystal with small refractive birefringence is refilled. The temperature effect on the linewidth is also investigated. The narrowest linewidth film is around 20.6 nm when refilled liquid crystal is heated up to the isotropic phase in our experiment. This reflective film can be used as the reflective layer in reflective display.

10125-39, Session 9

Smart windows using polymer-networked liquid crystals doped with push-pull azobenzene

Seung-Won Oh, Jong-Min Baek, Pusan National Univ. (Korea, Republic of); Sang-Hyeok Kim, Pusan National Univ (Korea, Republic of); Tae-Hoon Yoon, Pusan National Univ. (Korea, Republic of)

We propose a smart window using polymer-networked liquid crystal doped with push-pull azobenzene. Azobenzene is used to provide phase transition from the nematic to isotropic state through the trans-cis isomerization of azobenzene. When exposed to sunlight, the device switches from the opaque state (nematic phase) to the transparent state (isotropic phase). Switching from the transparent to opaque states can be obtained through rapid cis-trans isomerization of push-pull azobenzene without sunlight exposure. The proposed device can reduce the transmittance of the incident sunlight during daytime, whereas it can scatter the incident light during the night for privacy.

10125-40, Session 9

Electrothermo-optical effect in liquid crystals and its applications

Yu-Cheng Hsiao, Wei Lee, National Chiao Tung Univ. (Taiwan)

Technological revolutions have changed our life and society. Especially, manipulating light technology have been used as many products, strongly improve the human's life. In particular, the intensity of light through a liquid crystal (LC) can be managed by an electric field easily. Such a property is well known as the electro-optical (EO) effect. Accordingly, the commercial LC displays have been developed based on the EO effect. The effects of both magnetic and electric fields on nematic LCs have been investigated for a whole century. The first practical flat-panel LC display as a switchable light-valve device was reported by Heilmeier et al. However, comparing with EO effect, the electric field also can induce heat and affects the LC molecule flowing. In general, dielectric relaxation of LC is in high frequency range. However, dielectric heat can be easily generated in a type of special LC materials, called dual-frequency (DF) LCs. In a DF nematic LC (DFNLC), the orientational long-axis relaxation of the dielectric component occurs in the frequency range between 10 and 100 kHz. Consequently, the dielectric anisotropy shows its sign from positive to negative at a certain frequency called the crossover frequency fc. Furthermore, DF cholesteric LCs (DFCLCs) formed by mixing DFNLCs and chiral dopants have also been studied. No matter DFNLCs or DFCLCs, the dielectric heating effect may become significant when we operated the materials. Based on the DF mesophase, here we explore the joint thermodielectric and EO effects as a unique electrothermo-optical (ETO) effect. In comparison with the well-known EO characteristics of LCs, The ETO effect results in distinctive optical features, making them attractive for photonic applications.

10125-41, Session 9

Time-dependent deformation of polymer network in polymer-stabilized cholesteric liquid crystals

Kyung Min Lee, Vincent P. Tondiglia, Timothy J. Bunning, Timothy J. White, Air Force Research Lab. (United States)

Recently, we reported direct current (DC) field controllable electro-optic (EO) responses of negative dielectric anisotropy polymer stabilized cholesteric liquid crystals (PSCLCs). A potential mechanism is: Ions in the liquid crystal mixtures are trapped in/on the polymer network during the fast photopolymerization process, and the movement of ions by the application of the DC field distorts polymer network toward the negative electrode, inducing pitch variation through the cell thickness, i.e., pitch compression on the negative electrode side and pitch expansion on positive electrode side. As the DC voltage is directly applied to a target voltage, charged polymer network is deformed and the reflection band is tuned. Interestingly, the polymer network deforms further (red shift of reflection band) with time when constantly applied DC voltage, illustrating DC field induced time dependent deformation of polymer network (creep-like behavior). This time dependent reflection band changes in PSCLCs are investigated by varying the several factors, such as type and concentration of photoinitiators, liquid crystal monomer content, and curing condition (UV intensity and curing time). In addition, simple linear viscoelastic spring-dashpot models, such as 2-parameter Kelvin and 3-parameter linear models, are used to investigate the time-dependent viscoelastic behaviors of polymer networks in PSCLC.

10125-56, Session 9

Experimental realization of Bragg liquid crystal polarization gratings *(Invited Paper)*

Michael J. Escuti, Xiao Xiang, Jihwan Kim, North Carolina State Univ. (United States); Ravi K. Komanduri, ImagineOptix Corp. (United States)

We have successfully realized liquid crystal polarization gratings (PGs) with > 90% diffraction efficiency, at periods down to 335 nm, when illuminated with visible light. We have also realized experimentally the technique of slanting the grating vector using chiral dopants, effectively providing a complete and compelling analog to conventional Bragg volume holograms. Bragg PGs employ geometric phase, also called the Pancharatnam-Berry phase, rather than the conventional dynamic phase, and this leads to unique and often unexpected optical behavior. In one configuration, these gratings will diffract first-order light into high-index waveguide angles from on-axis directions, or alternatively, can produce wide chromatic dispersion into air. We employ photo-aligned reactive mesogens, also called liquid crystal polymer networks, and both spin-coating and holographic lithography. While liquid crystal PGs with relatively large periods (≥ 2 μm) were realized with high efficiency over the past decade, small period liquid crystal PGs (< 1 μm) were considered by some to have several fundamental challenges making them experimentally impossible. However, we have overcome these challenges. In this talk, we will discuss how we have done so, report on the experimental behavior of these Bragg PGs including their spectral, field-of-view (FOV), and polarization, and discuss the vast array of applications now possible, including head-mounted-displays, blazed gratings for spectroscopy and telecom, beam combining, and optical remote sensing.

10125-58, Session 9

Smectic hybrid oligo(dimethylsiloxane) liquid crystal for nanopatterning *(Invited Paper)*

Koen Nickmans, Albertus P. H. J. Schenning, Technische Univ. Eindhoven (Netherlands)

We have recently developed monodisperse oligo(dimethylsiloxane) liquid crystals which form ordered phases on the order of several nanometers with inherently low defectivities, making them highly suitable for nanopatterning applications. Moreover, the features can be easily aligned by lithographic guiding structures resulting in highly ordered nanopatterns, without the need for additional annealing, and multiple times smaller than previously reported.

10125-51, Session PWed

Liquid crystal gratings for advanced control of polarized light propagation fabricated by one-step multiple beam holographic photoalignment

Kotaro Kawai, Moritsugu Sakamoto, Kohei Noda, Tomoyuki Sasaki, Nagaoka Univ. of Technology (Japan); Nobuhiro Kawatsuki, Univ. of Hyogo (Japan); Hiroshi Ono, Nagaoka Univ. of Technology (Japan)

Control of various parameters of a light wave, such as amplitude, polarization, wavelength, and propagation direction is of importance in the optoelectronics field. Liquid crystal (LC) gratings, in which the LC directors are periodically distributed in the cell, are one of the diffractive optical elements which satisfy such a function. To improve conventional problems as the complexity in fabrication processes, we have proposed the efficient yet practical method for fabricating the LC gratings using a photocrosslinkable polymer LC (PCLC) synthesized by us. The in-plane alignment direction of PCLC can be controlled depending on the exposure dose of linearly polarized UV light. By applying this alignment property, 90° twisted nematic and 0° planar alignment structures can be fabricated by simultaneously irradiating an empty glass cell composed of two PCLC films with a linearly polarized UV beam. In this presentation, we report the fabrication of LC gratings with three-dimensionally modulated anisotropic structures by one-step exposure of an empty glass cell to three-beam and four-beam polarization interference UV beams. The polarization diffraction properties were measured experimentally by the incidence of visible lasers, and analyzed theoretically by Jones calculation. The polarization azimuth, ellipticity, propagation direction, and polarization rotation direction of the diffracted beams from the resultant LC gratings widely varied depending on the two-dimensional diffracted position, the polarization states and the wavelength of the incident beams. They are expected to apply to diffractive optical elements for advanced control of polarized beams, such as polarization conversion, separation, and optical switching.

10125-52, Session PWed

Photo-controllable reflection notch tuning and bandwidth broadening in polymer stabilized cholesteric liquid crystals

Kyung Min Lee, Vincent P. Tondiglia, Timothy J. Bunning, Timothy J. White, Air Force Research Lab. (United States)

We have recently reported on direct current (DC) field controllable electro-optic (EO) responses of the reflection band of polymer stabilized cholesteric liquid crystals (PSCLCs) including bandwidth broadening, switchable scattering, and red-shifting tuning. The position or bandwidth of the selective reflection of PSCLCs prepared from negative dielectric anisotropy liquid crystalline hosts can be controlled by the application of a DC voltage. Here, we report that these EO responses of PSCLCs can also be tuned by UV light at constantly applied DC voltage. Measurement of the ion density of a series of control compositions during irradiation with UV light confirms that the ion density in compositions that exhibit photosensitivity is increased by irradiation. The ion density in the LC mixtures is dependent on not only the concentration of the photoinitiator but also the type. Thus, the magnitude of the electrically tuned or broadened reflection of PSCLC of certain compositions when subjected to DC field is further increased in the presence of UV light.

10125-53, Session PWed

Fabrication of anisotropic diffractive optical element by using polarization drawing method based on galvanometer scanner

Kohei Noda, Jou Matsubara, Kotaro Kawai, Moritsugu Sakamoto, Tomoyuki Sasaki, Hiroyuki Okamoto, Nagaoka Univ. of Technology (Japan); Nobuhiro Kawatsuki, Univ. of Hyogo (Japan); Kohei Goto, Nissan Chemical Industries, Ltd. (Japan); Hiroshi Ono, Nagaoka Univ. of Technology (Japan)

Polarization is one of the important parameters of the light wave. Diffractive elements, which can control the polarization, have been attracted as high-performance light control device. We have implemented various studies on the formation method and the diffraction characteristics of the anisotropic diffractive element using a photoreactive material. Photocrosslinkable polymer liquid crystal (PCLC) is an attractive material that can induce anisotropy along the polarization direction of linearly polarized ultraviolet light (LPUV). Also, owing to its relatively large anchoring strength, PCLC have been used as alignment film of low-molar-mass liquid crystal (LC).

Galvanometer scanners (GS) can freely control the exposure position of the laser beam by adjusting the two mirrors, it is possible to form a highly functionalized optical element by drawing the arbitrary exposure lines to the photo-reactive material with temporally changing the polarization state of the laser beam.

In this study, we report the polarization drawing method based on GS for the fabrication of anisotropic diffractive optical elements. First, two types anisotropic diffractive optical elements were fabricated on the PCLC films. To investigate the diffraction properties of fabricated anisotropic diffractive optical elements, we used a polarized He-Ne laser beam as probe and observed diffracted lights. Diffracted beam was two-dimensionally emitted depending on the formed anisotropic optical distribution. Then we fabricated LC cell, which works as polarization dependent anisotropic Fresnel lens. The experimental investigations show that it has functions of light condensing and polarization control. From these results, high-performance light control device can be fabricated by polarization drawing method.

10125-54, Session PWed

Temperature-independent zero-zero-birefringence polymer for liquid-crystal displays

Hiroaki Nagahama, Mio D. Shikanai, Keio Univ. (Japan); Akihiro TAGAYA, Yasuhiro Koike, Keio Univ. (Japan) and Keio Photonics Research Institute (Japan)

In the case of a typical thermoplastic polymer used for low birefringent optical films in liquid crystal displays, the major types of birefringence are orientational birefringence and photoelastic birefringence. Polymers exhibiting no birefringence can be obtained by randomly copolymerizing positive and negative birefringent monomers. Focusing on intrinsic birefringence and photoelastic coefficient of each polymer, zero–zero-birefringence polymers (ZZBPs) exhibiting neither orientational birefringence nor photoelastic birefringence are synthesized by designing the constituents and the composition ratios to make intrinsic birefringence and photoelastic coefficient cancel each other out. However, recently we found that ZZBPs exhibit birefringence at other than the room temperature because their constituents have inherent temperature dependence of intrinsic birefringence. We therefore proposed a temperature-independent zero–zero-birefringence polymer (TIZZBP) exhibiting neither orientational birefringence nor photoelastic birefringence over a wide temperature range, and the purpose of this article is to synthesize a TIZZBP.

Temperature dependence of intrinsic birefringence can also be canceled each other out by randomly copolymerizing positive and negative temperature-dependent constituents. Therefore, we evaluated intrinsic birefringence ?n0, photoelastic coefficient C, and temperature coefficient of intrinsic birefringence d?n0/dT of various polymers, and estimated a composition of a TIZZBP by calculation to obtain ?n0=C=d?n0/dT=0 based on the evaluated values. Synthesizing copolymers with multiple compositions around the calculated composition, we obtained poly(methyl methacrylate/benzyl methacrylate/isobornyl methacrylate/N-ethyl maleimide=34/24/41/1 (wt. %)) that exhibits almost no orientational birefringence, almost no photoelastic birefringence, and almost no temperature dependence of these types of birefringence. Based on the above, a TIZZBP was demonstrated for the first time.

10125-55, Session PWed

Blood shear stress sensor employing liquid crystals

Alaeddin S. Abuabed, Univ. of Central Oklahoma (United States)

For decades, the measurement of the blood shear stress (BSS) has been a topic of great interest for many of diagnostics applications. Monitoring and measuring the wall shear stress in blood vessels is critical in studying and diagnosing various diseases. Several mathematical and experimental models have been developed as efforts to study the hemodynamic of blood, in particular the blood wall shear stress. Recent studies have shown that wall shear stress is closely related to the development of arteriosclerosis disease which seriously affects the human health. This paper presents an alternative mechanism that involves liquid crystal to measure BSS. In this work, the author has developed a new method which utilizes LC film embedded in a capacitive microstructure. This innovation will transduce the blood shear force, which deforms the LC profile, into a measurable capacitive quantity via tracking the LC deformation. This promising sensor has strong potential applications in carotid artery experiments. Some of the issues addressed in this work are the impact of the blood shear stress on the liquid crystal molecular ordering and the influence of capacitance geometry and material properties on the measured capacitances. The proposed mechanism offers remarkable advantages over the conventional visual inspection optical methods. For example, it provides greater insight into the fundamental distortion occurring in the LC film due to the blood shear stress force, and offers the ability to identify and track the average deformation. In addition, a simpler system with autonomous operation and reduced possible false alarms is achievable.

10125-43, Session 10

Holographic and light-field imaging for augmented reality *(Invited Paper)*

Byoungho Lee, Jong-Young Hong, Changwon Jang, Seungjae Lee, Seoul National Univ. (Korea, Republic of)

Virtual reality (VR) and augmented reality (AR) have been studied a lot as an emerging technology nowadays. There have been various approaches to realize the VR and AR by providing the virtual image to the human eye. Hence, various methods of three-dimensional (3D) display have been researched including integral imaging, multi-view display, volumetric display which are represented by the light field imaging in these days, and holographic display. With those technologies, various VR products have been already released. However, the AR display is not ready for the prime time yet because it needs the see-through property in addition to providing 3D image to the user.

In this invited presentation, we focus on various kinds of see-through 3D display to provide the AR to the user using light field imaging and holographic display. To make light field display have see-through property, the convex-half-mirror-array (CHMA) has been proposed in our previous work. With the index matching technology, the real world information passes through clearly, while the projected 3D image is converged by the half-mirror coated lens array based on the principle of the integral imaging. To give high resolution see-through 3D display, the combination of multi-projection and index-matched holographic diffuser is also proposed. Besides, holographic optical elements (HOEs) have been studied a lot as a good candidate of the AR display. Under the holographic recording principle, the transparent photopolymer can operate as various kinds of optical elements such as diffuser, lens, and lens array. With those HOEs, various applications such as see-through integral imaging, 2D/3D convertible display and near-eye display have been proposed. In addition, we will discuss on our recent see-through layered display with HOEs.

10125-44, Session 10

Recent advances in head-mounted light field displays for virtual and augmented reality *(Invited Paper)*

Hong Hua, The Univ. of Arizona (United States)

Head-mounted light field displays render a true 3D scene by sampling either the projections of the 3D scene at different depths or the directions of the light rays apparently emitted by the 3D scene and viewed from different eye positions. They are capable of rendering correct or nearly correct focus cues and addressing the very well-known vergence-accommodation mismatch problem in conventional virtual and augmented reality displays. In this talk, I will focus on reviewing recent advancements of head-mounted light field displays for VR and AR applications. I will demonstrate examples of HMD systems developed in my group.

10125-45, Session 10

Focus-tunable and fixed lenses and stereoscopic 3D displays *(Invited Paper)*

Martin S. Banks, Univ. of California, Berkeley (United States); Paul V. Johnson, Apple Inc. (United States); Joohwan Kim, NVIDIA Corp. (United States); George A. Koulieris, George Drettakis, INRIA Sophia Antipolis - Méditerranée (France); Jared A. Q. Parnell, Gordon D.

Love, Durham Univ. (United Kingdom)

Stereoscopic 3D (S3D) displays provide an enhanced sense of depth by sending different images to the two eyes. But these displays do not reproduce focus cues (blur and accommodation) correctly. Specifically, the eyes must accommodate to the display screen to create sharp retinal images even when binocular disparity drives the eyes to converge to other distances. This mismatch causes discomfort, reduces performance, and distorts 3D percepts. We developed two techniques designed to reduce vergence-accommodation conflicts and thereby improve comfort, performance, and perception. One uses focus-tunable lenses between the display and viewer's eyes. Lens power is yoked to expected vergence distance creating a stimulus to accommodation that is consistent with the stimulus to vergence. This yoking should reduce the vergence-accommodation mismatch. The other technique uses a fixed lens before one eye and relies on binocularly fused percepts being determined by one eye and then the other, depending on simulated distance. This is meant to drive accommodation with one eye when simulated distance is far and with the other eye when simulated distance is near. We conducted performance tests and discomfort assessments with both techniques and with conventional S3D displays. We also measured accommodation. The focus-tunable technique, but not the fixed-lens technique, produced appropriate stimulus-driven accommodation thereby minimizing the vergence-accommodation conflict. Because of this, the tunable technique yielded clear improvements in comfort and performance while the fixed technique did not. The focus-tunable lens technique therefore offers a relatively easy means for reducing the vergence-accommodation conflict and thereby improving viewer experience.

10125-46, Session 10

Wide color gamut LCDs with organic-inorganic perovskite-polymer composite films

Juan He, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Yanan Wang, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Beijing National Lab. for Molecular Sciences (China); Hao Chen, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and NanoScience Technology Ctr., Univ. of Central Florida (United States); Jiangshan Chen, NanoScience Technology Ctr., Univ. of Central Florida (United States) and Changchun Institute of Applied Chemistry (China); Ruidong Zhu, Shin-Tson Wu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Yajie Dong, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and NanoScience Technology Ctr., Univ. of Central Florida (United States) and Univ. of Central Florida (United States)

Recently, organic-inorganic perovskite (OIP) emerges as promising light emitting materials with high efficiency and superb color purity. Despite the astonishing progress, instability under external stress like moisture, oxygen, heat, etc. remains one of the biggest challenges to overcome. The simple swelling-deswelling microencapsulation strategy reported in this paper overcomes the major instability challenge for OIP materials and a series of ultrastable, highly luminescent CH3NH3PbBr3 OIP - polymer composite films with great dispersion and intimate passivation of crystalline OIP nanoparticles within polymer matrix have been achieved. This process yields composite films with high PLQY of up to 48%, high color purity showing FWHM down to 18 nm, and long average fluorescence lifetime (?avg) up to ~502 ns. The OIP-polymer composite films can stand boiled water, showing unprecedented water and heat stability. To apply these films as downconverters for the backlight unit (BLU) of liquid crystal displays (LCDs), a green CH3NH3PbBr3-PS film and a red CdSe based QD - polymer film were pumped by a high power blue LED (450 nm with a FWHM of 20 nm). The resultant spectrum after color filters can cover 90% of the Rec. 2020 color gamut. If combined with Mn4+ activated red phosphors rather than QDs, 89% coverage can be obtained. Compared to commercialized all-QDs approach, our hybrid film using green OIP and red QDs/phosphors has the advantage of narrower linewidth thus higher color purity, easier process and much lower cost.

10125-57, Session 10

Application of LC and LCoS in Multispectral Polarized Scene Projector (MPSP) *(Invited Paper)*

Haiping Yu, Lei Guo, Shenggang Wang, Jack R. Lippert, Le Li, Kent Optronics, Inc. (United States)

A Multispectral Polarized Scene Projector (MPSP) had been developed in the short wave infrared (SWIR) regime for the test & evaluation (T&E) of spectro-polarimetric imaging sensors. This MPSP generates multispectral and hyperspectral video images (up to 200 Hz) with 512?512 spatial resolution with active spatial, spectral, and polarization modulation with controlled bandwidth. It projects input SWIR radiant intensity scenes from stored memory with user selectable wavelength and bandwidth, as well as polarization states (six different states) controllable on a pixel level. The spectral contents are implemented by a tunable filter with variable bandpass built based on liquid crystal material. The core of the MPSP hardware is the liquid-crystal-on-silicon (LCoS) spatial light modulators (SLMs) for intensity control and polarization modulation.

10125-47, Session 11

Fast-response LCDs for virtual reality applications *(Invited Paper)*

Haiwei Chen, Fenglin Peng, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Fangwang Gou, CREOL, The College of Optics and Photonics, Univ. of Central Florida (China); Michael D. Wand, LC Vision, LLC (United States); Shin-Tson Wu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Virtual reality is an emerging wearable display technology with potential applications for entertainment, education, training, design, advertisement, and medical diagnostics. Both liquid crystal display (LCD) and organic light-emitting diode (OLED) are applicable for such kind of head-mounted display applications. Currently, OLED is a favored choice due to its fast response time, which helps to suppress motion image blur noticeably. However, OLED has some drawbacks, such as inadequate lifetime and resolution density. LCD offers high resolution, high brightness, long lifetime and low cost, but its response time is about 100X slower than OLED's. As a result, LCD is generally perceived to exhibit much more severe image blurs than OLED. In this paper, we find that image blurs, quantified by motion picture response time (MPRT), are mainly governed by thin-film transistor (TFT) frame rate if the LC (or OLED) response time is less than 2 ms (at 120 Hz). Based on this finding, we developed an ultra-low-viscosity LC mixture for vertical alignment (VA) mode, whose average gray-to-gray (GTG) response time is only 1.29 ms. With these results, the obtained average MPRT is 6.88 ms, which is comparable to 6.66 ms for an OLED at a 120 Hz frame rate. By slightly increasing the TFT frame rate and/or reduce the backlight duty ratio, image blurs can be further suppressed to unnoticeable level, making LCD a strong contender for virtual reality, gaming monitor and TV applications.

10125-48, Session 11

Experimental studies on liquid-crystal micro-droplets for optical micro-resonators and micro-lasers *(Invited Paper)*

Surajit Dhara, Univ. of Hyderabad (India)

Optical microresonators are very useful because of their small mode volumes and high quality factors. Recently such studies have drawn significant attention because of the potential application of these microresonators in various fields. Mostly solid dielectric microspheres are preferred for studying optical resonance or lasing. In this talk I will present and discuss some of our recent results on the whispering gallery resonance (WGM) and lasing from liquid crystal micro-droplets. We show that WGM resonance can be used for detecting weak phase transitions in liquid crystals. The resonance can also be tuned by external weak magnetic field in ferronematic liquid crystals micro-droplets.

10125-49, Session 11

Improved nanoparticle-doped liquid crystals for holographic 3D displays *(Invited Paper)*

Jicheng Liu, Hongyue Gao, Shanghai Univ. (China)

Holographic 3D display is a true 3D display technology, which can provide realistic 3D images without any special eyewear for observers. It may be ultimately developed into holographic 3D televisions and holographic 3D projectors. Static holographic 3D display or holograms stored in materials has shown a perfect 3D display of holography. However, dynamic holography has not been applied in 3D video display because of limitations of current holographic display devices-spatial light modulators and slow-response dynamic holographic materials with hologram refresh rate, less than 25 Hz. We achieved real-time dynamic holographic 3D display in nanoparticles doped liquid crystal films Holographic 3D video display with refresh rate, more than 25 Hz, was realized using them. Moreover, they are easier to fabricate large-size color video-rate holographic 3D display screens by using these materials. We have and built holographic video display systems using these nanoparticles doped liquid crystal films as screens. This paper will focus on property and holographic 3D video display of the nanoparticles doped liquid crystals, and present their potential applications in large-size, high-definition, and color holographic true 3D video displays.

10125-50, Session 11

Wide-temperature high-speed operation of a nematic liquid-crystal cell

Tae-Hoon Choi, Jung-Wook Kim, Tae-Hoon Yoon, Pusan National Univ. (Korea, Republic of)

Short response time is one of the most critical requirements for liquid crystal display (LCD) devices because it helps reduce motion blur in fast moving pictures and provide a clear image without distortion. However, an LCD suffers from the drawback of slow response, especially at low temperature. As the temperature decreases, the response time of an LCD increases considerably because of the increased rotational viscosity of the LCs. This leads to serious problems when LCD devices are used under low-temperature outdoor environments. There is an urgent need to reduce this response time for outdoor applications, such as digital signage and automotive displays, over a wide temperature range. In this presentation, we report wide-temperature, high-speed operation of a nematic LC cell for outdoor applications. Switching between all gray levels is forcibly controlled by applying an electric field so that the slower response time at low temperature can be compensated by a higher electric field, resulting in fast switching of the LCs irrespective of the ambient temperature. In addition to providing a fast response, it retains the high transmittance characteristics of a fringe-field-switching LC cell.

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10126-17, Session PWed

Advanced wavefront correction of spatial light modulator under temperature-varying conditions

Yu Takiguchi, Tomoko Otsu-Hyodo, Takashi Inoue, Haruyoshi Toyoda, Hamamatsu Photonics K.K. (Japan)

Conventional methods of compensating for self-distortion in liquid-crystal-on-silicon spatial light modulators (LCOS-SLM) are based on aberration correction, where the wavefront of the incident beam is modulated to compensate for aberrations caused by the imperfect optical flatness of the LCOS-SLM surface. Previously, we proposed an effective method to compensate for the distortion by displaying a compensation phase pattern obtained from interferometry However, the phase distribution of an LCOS-SLM varies with changes in ambient temperature and requires additional correction. The ambient temperature of LCOS-SLMs can vary under certain circumstances, i.e. equipped inside systems for field use or long-term operations.

In this presentation, a novel phase compensation method under temperature-varying conditions based on an orthonormal Legendre series expansion of the phase distribution. We found several Legendre coefficients that follow quadratic functions of ambient temperature. This prompted us to propose an algorithm for correcting the temperature dependency by displaying a phase pattern using two simple steps: an initializing step and a temperature correction step. We investigated the temperature dependency by controlling the ambient temperature with an incubator and successfully corrected for self-distortion in a temperature range of approximately 68?F to 122?F, giving an optical flatness of <? /10. Our approach has the potential to be adopted in tight-focusing applications which require wavefront modulation with very high accuracy. Additionally, the concept of this method is extensible to the thermal behavior of other optical devices, such as lenses and mirrors, which have the possibility of causing unexpected aberrations.

10126-18, Session PWed

Improved outcoupling efficiency of organic light-emitting diodes by spontaneously formed internal wrinkle structure: a radiation out-coupling case

Jong Chan Jeong, Electronics and Telecommunications Research Institute (Korea, Republic of); Jin-Wook Shin, Electronics and Telecommunications Research Institute (Korea, Republic of) and Tohoku Univ. (Japan); Jonghee Lee, Chul Woong Joo, Hyunsu Cho, Jun-Han Han, Jeong-Ik Lee, Nam Sung Cho, Jaehyun Moon, Electronics and Telecommunications Research Institute (Korea, Republic of); Eungjun Kim, Seunghyup Yoo, KAIST (Korea, Republic of); Jun-Hwan Park, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of); SungYun Yang, Chungnam National Univ. (Korea, Republic of)

Due to the presence of various waveguiding modes and surface plasmons polariton losses, the external quantum efficiencies of conventional organic light emitting diodes (OLEDs) cannot exceed 30%, posing a significant hurdle in general light management. The efficiency can be enhanced by light extraction methods, which not only lead to energy saving but also device life time lengthening. Thus there is a technical need to enhance the efficiency. In this regard several methods have been suggested to retrieve the wasted light. In this work, we present wrinkle as an OLEDs light extraction structure. Our wrinkles are formed spontaneously from a UV cured prepolymer, obviating the need of patterning process. Wrinkles are positioned between the substrate and the IZO/Organics, giving a wavy OLEDs shape. Unlike existing internal light extraction structures of which sizes are in visible wavelength scale, our wrinkles are in micron size range that period and amplitude are 2.76 ?m and 0.88 ?m, respectively. By the use of our internal micron size wrinkles, it is possible to out-couple the confined light by a radiation mode. This is in contrast to scattering mechanism, which is dominantly present at visible length scale. To experimentally verify our approach, we have fabricated bottom emission type OLEDs equipped with internal micron size wrinkles. By equipping OLEDs with internal wrinkles, compared with efficiencies of planar OLEDs, it was possible to enhance the external quantum efficiency and luminance efficiency by 32% and 47%, respectively. Our method present a new structure which give the emergence of radiation out-coupling. Our approach is not limited to OLED but readily applicable to optical and photonic applications in which the extraction of confined light matters.

10126-19, Session PWed

Design of a liquid-crystal display with surface-diffusing system using a collimated direct backlight

Haruka Suzuki, Akihiro Tagaya, Yasuhiro Koike, Keio Univ. (Japan)

Improvement of endoscope monitors such as smaller color shift, higher contrast, and higher definition is important for precise surgery. There are two main systems for a liquid crystal display (LCD) with a wide viewing angle. One is used in conventional LCDs. The other is surface diffusing system (SDS) to diffuse lights from a collimated backlight by a scattering film placed on the surface of the LCD. The LCD with SDS (SDS-LCD) shows smaller color shift than conventional LCDs. However, the SDS-LCD is not put to practical use because of the image blurring by the scattering film. We propose the SDS-LCD using a collimated direct backlight to meet requirements for endoscope monitors. We design a collimated direct backlight for the SDS-LCD to suppress the image blurring. Using three backlights with luminance angular distributions of 20, 30, and 90 degrees (FWHM), we showed that the image sharpness and the contrast ratio of the 78-ppi (4K, 55inch equivalency) VA mode SDS-LCD became high with increasing the directionality of the backlight. Therefore, a basic unit of a collimated direct backlight with a luminance angular distribution of 10 degrees (FWHM) was fabricated with directional cannonball type LEDs and optical homogenizers. The 78-ppi VA mode SDS-LCD using the basic unit showed few blurs of the image and color shift less than 0.02. A collimated direct backlight for the SDS-LCD can be designed by tiling the basic unit because the basic unit is a surface light source having high uniformity of color and luminance.

10126-20, Session PWed

High-efficiency multiple-light-source red-green-blue power combiner with optical waveguide mode-coupling technique

Junji Sakamoto, Satomi Katayose, Kei Watanabe, Nippon Telegraph and Telephone Corp. (Japan); Mikitaka Itoh, NTT Photonics Labs. (Japan); Toshikazu Hashimoto, Nippon Telegraph and Telephone Corp. (Japan)

We propose a very low loss multiple-light-source red (R)-green (G)-blue (B) power combiner using an optical waveguide mode coupling technique.

The combiner consists of a two-stage circuit, which works for both power coupling and wavelength multiplexing for multiple-light-source of RGB colors. The first-stage of the circuit combines RGB light as the 0th order mode using directional couplers. The second stage combines other R and G light with mode-conversion from the 0th order mode to second order modes using waveguide mode couplers. We adopt an even mode configuration to avoid asymmetric deformation of the beam due to interference between the modes. Using all of these coupler functions in the two stages, the circuit provides multiple-light-source (RRGGB) power combining. The combiner was fabricated with a silica planar lightwave circuit (PLC) technology. The circuit is about 8-mm long, including 6 mm for the 0th order coupler and 2 mm for second order coupler. We estimated the coupling loss of both the 0th order RGB coupler and second order RG coupler to be about 1 dB by evaluating the combined power for 0th order RGB couplers and the complementary output powers for mode couplers. This is the first demonstration of a multiple-light-source RRGGB power combiner using multimode coupling. This method enables us to combine much larger number of light sources using multi-stage coupling for different modes as well. Moreover, the beam shape can be controlled by mode selection.

10126-21, Session PWed

Dual Purpose Passive Screen for Simultaneous Display and Imaging

Shoaib Rehman Soomro, Erdem Ulusoy, Muhsin Eralp, Hakan Urey, Koç Univ. (Turkey)

3D imaging and display techniques are widely explored for realistic content capture and visualization but cannot fully follow the miniaturisation and mobility trends in technology. Wide field-of-view displays require immobile surfaces and 3D image capture requires fixed installations of distributed sensor arrays. Here we propose a novel, portable dual purpose passive screen that can simultaneously facilitate display and 3D imaging with unprecedented features and performance. The proposed screen is made up of two integrated optical surfaces. The first optical surface is a projection surface, which consists of finely patterned retro-reflective microspheres that provide high optical gain and transparency. The second optical surface is an imaging medium made up of an array of reflective lenses, which can form the virtual 3D perspective views of the real world scene. When coupled with a high-resolution camera, the imaging surface enables 3D image/lightfield capture as though there is an array of cameras. An optional intermediate polarization selective layer between two surfaces also enables parallel display and imaging operation. The optical design of the screen is presented. A prototype of the dual purpose screen paired with high resolution camera and low power mobile projector is demonstrated. The developed screen has size of 28x21cm2 to facilitate capture of 4x3 array of perspective images and display high-quality images with high-brightness (>100cd/m2 achievable) using only 15 lumens pico-projector.

10126-23, Session PWed

Aerial secure display by use of polarization-processing display with retarder film and retro-reflector

Shusei Ito, Keitaro Uchida, Utsunomiya Univ. (Japan); Haruki Mizushina, Shiro Suyama, The Univ. of Tokushima (Japan); Hirotsugu Yamamoto, Utsunomiya Univ. (Japan)

[CONTEXT] Security is one of the big issues in automated teller machine (ATM). In ATM, two types of security have to be maintained. One is to secure displayed information. The other is to secure screen against contamination. In order to secure information against peeping at the screen, we have proposed secure display by use of visual cryptography [H. Yamamoto, Opt. Lett. 28, 1564 (2003)]. Aerial information screen with aerial imaging by retro-reflection, named AIRR [H. Yamamoto, Opt. Exp. 22, 26919 (2014)] is a prospective technique to avoid direct touch on a screen. [OBJECTIVE] The purpose of this paper is to propose an aerial secure display technique that ensures security of displayed information as well as security against contamination problem on screen touch. [METHOD] We have developed a polarization-processing display that is composed of a backlight, a polarizer, a background LCD panel, a gap, a half-wave retarder, and a foreground LCD panel. Polarization angle is rotated with the LCD panels. We have constructed a polarization encryption code set. Size of displayed images are designed to limit the viewing position. Furthermore, this polarization-processing display has been introduced into our aerial imaging optics, which employs a reflective polarizer and a retro-reflector covered with a quarter-wave retarder. Polarization-modulated light forms the real image over the reflective polarizer. [RESULTS] We have successfully formed aerial information screen that shows the secret image with a limited viewing position. [NOVELTY] This is the first realization of aerial secure display by use of polarization-processing display with retarder-film and retro-reflector.

10126-24, Session PWed

Hybrid display of static image and aerial image by use of transparent acrylic cubes

Shogo Morita, Shusei Ito, Hirotsugu Yamamoto, Utsunomiya Univ. (Japan)

[CONTEXT] Aerial display can form transparent floating screen in the mid-air and expected to provide aerial floating signage. We have proposed aerial imaging by retro-reflection (AIRR) [H. Yamamoto, Opt. Exp. 22, 26919 (2014)] to form a large aerial LED screen. However, luminance of aerial image is not sufficiently high so as to be used for signage under broad daylight. [OBJECTIVE] The purpose of this paper is to propose a novel aerial display scheme that features hybrid display of two different types of images. Under daylight, signs made of cubes are visible. At night, or under dark lighting situation, aerial LED signs become visible. [METHOD] Our proposed hybrid display is composed of an LED sign, a beam splitter, retro-reflectors, and transparent acrylic cubes. Aerial LED sign is formed with AIRR. Furthermore, we place transparent acrylic cubes on the beam splitter. Light from the LED sign enters transparent acrylic cubes, reflects twice in the transparent acrylic cubes, exit and converge to plane-symmetrical position with light source regarding the cube array. Thus, transparent acrylic cubes also form the real image of the source LED sign. Now, we form a sign with the transparent acrylic cubes so that this cube-based sign is apparent under daylight. [RESULTS] We have developed a proto-type display by use of 1-cm transparent cubes and retro-reflective sheeting and successfully confirmed aerial image forming with AIRR and transparent cubes as well as cube-based sign under daylight. [NOVELTY] This is the first proposal on hybrid image of static image and aerial image.

10126-25, Session PWed

Improvement of 3D surface reconstruction using fringe projection by Talbot effect and extended Fourier transform

Mauricio Ortiz-Gutiérrez, Rafael González-Campos, Marco Antonio Salgado-Verduzco, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); Mario Pérez-Cortés, Univ. Autónoma de Yucatán (Mexico); Arturo Olivares-Pérez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Juan Carlos Ibarra-Torres, Univ. de Guadalajara (Mexico); Jennifer López-Chacón, Univ. Michoacana de San Nicolás de Hidalgo (Mexico)

The 3D surface reconstruction is done by analyzing the deformation of the image of binary grating projected onto the relief of an object, after that, the phase of the deformed pattern is extracted by Fourier transform and unwrapping the phase. There are several techniques for image grating

projection and one of them is the so called Talbot Effect that creates self-images of a binary gratings. In this work one of the self-image of a grating is used for projection on the relief of an object. The deformed image is captured by a camera and is analyzed by a Fourier Transform algorithm proposed called Extended Fourier Transform (XFT). The XFT algorithm is an enhancement of the common FFT algorithm and allows an improvement in surface reconstruction. A comparison between the reconstructed surfaces using traditional FFT algorithm and the proposed XFT algorithm is presented.

10126-26, Session PWed

Design of an ultra-thin near-eye display with geometrical waveguide and freeform optics

Meng-Che Tsai, Tsung-Xian Lee, National Taiwan Univ. of Science and Technology (Taiwan)

Due to the worldwide portable devices and illumination technology trends, researches interest in laser diodes applications are booming in recent years. One of the popular and potential LDs applications is near-eye display used in VR/AR. An ideal near-eye display needs to provide high resolution, wide FOV imagery with compact magnifying optics, and long battery life for prolonged use. However, previous studies still cannot reach high light utilization efficiency in illumination and imaging optical systems which should be raised as possible to increase wear comfort.

To meet these needs, an ultra-thin near-eye display with geometrical waveguide and freeform optics is presented in this paper. We propose a high efficiency RGB LDs light engine which could reduce the volume and power consumption by using freeform reflectors instead of beam splitters and also keep good color uniformity. We also demonstrate a new imaging system design composed by geometrical waveguide and freeform optical elements with little parasitic light and scattering light. By these structures, the total system size of near-eye display is successfully decreased, and the improved results in resolution and retinal imaging quality of near-eye displays are shown in this paper.

10126-1, Session 1

The design considerations for full-color e-paper *(Invited Paper)*

Bo-Ru Yang, Yu-Cheng Wang, Li Wang, Sun Yat-Sen Univ. (China)

Flexible display has been considered as one of the most important components to realize the applications of internet of things (IoTs). Among all the display technologies, the electrophoretic type of E-Paper is the most mature technology in terms of mass-production. Applications of E-book, E-tag, and electronic shelf label (ESL) are prevailing in the consumer markets. However, to further promote the application of E-Paper, it is very necessary to achieve full-color. In this paper, we would like to review the status of color E-Paper technologies, and the insightful theories and design considerations will be discussed.

10126-2, Session 1

Design of a backlighting structure for very large-area luminaries

Luca Carraro, Univ. degli Studi di Pavia (Italy); Aki P. Mäyrä, VTT Technical Research Ctr. of Finland Ltd. (Finland); Marcello Simonetta, Guido Benetti, Alessandro Tramonte, Univ. degli Studi di Pavia (Italy); Mauro Benedetti, Enrico M. Randone, Julight S.r.l (Italy); Arto Ylisaukko-Oja, Kimmo Keränen, VTT Technical Research Ctr. of Finland Ltd. (Finland); Tullio Facchinetti, Guido Giuliani, Univ. degli Studi di Pavia (Italy)

A novel approach for RGB semiconductor LED-based backlighting system is developed to satisfy the requirements of the Project LUMENTILE funded by the European Commission, whose scope is to develop a luminous electronic tile that is foreseen to be manufactured in millions of square meters each year. This unconventionally large-area surface of uniform, high-brightness illumination requires a specific optical design to keep a low production cost, while maintaining high optical extraction efficiency and a reduced thickness of the structure, as imposed by architectural design constraints.

The proposed solution is based on a light-guiding layer to be illuminated by LEDs in edge configuration, or in a planar arrangement. The light guiding slab is finished with a reflective top interface and a diffusive or reflective bottom interface/layer. Patterning is used for both the top interface (punctual removal of reflection and generation of a light scattering centers) and for the bottom layer (using dark/bright printed pattern). Computer-based optimization algorithms based on ray-tracing are used to find optimal solutions in terms of uniformity of illumination of the top surface and overall light extraction efficiency. Through a closed-loop optimization process, that assesses the illumination uniformity of the top surface, the algorithm generates the desired optimized top and bottom patterns, depending on the number of LED sources used, their geometry, and the thickness of the guiding layer.

Specific low-cost technologies to realize the patterning are discussed, with the goal of keeping the production cost of these very large-area luminaries below the value of 100$/sqm.

10126-3, Session 1

New generation of Fourier optics viewing angle measurement systems

Pierre M. Boher, Thierry Leroux, Vincent Leroux, Thibault Bignon, Veronique Collomb-Patton, ELDIM (France)

Viewing angle properties are certainly the most common characteristics measured on displays. Historically, the goniometer was the first equipment used to perform such angular measurements [1]. In 1992 ELDIM introduced an optical Fourier transform (OFT) system with a specific optic in order to convert angular field map into a planar one to allow rapid and precise measurements [2-3]. The theoretical [4] and practical advantages of this technology with regards to goniometers or hemisphere based imagers has long been recognized. Since then, this type of system has been used by all major companies. Along the years the system has seen main developments and improvements for different specific applications: large angular aperture systems with spot size up to 6mm [5], multispectral systems [6], high angular resolution systems for 3D displays [7] and polarization analysis [8] have been successively proposed.

In the present paper, we will introduce a new generation of OFT systems with new characteristics. In spite of a more compact size, the optic shows better performances in terms of resolution and collection efficiency. The detection is made with a new generation high resolution CMOS camera which allows much shorter measurement times. In addition, the probe is much smaller and can be used on a robotic arm. It gives a versatile and cost effective solution for quality control of any display size and geometry.

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10126-4, Session 1

Photoluminescent (PL) or electroluminescent (EL) quantum dots for display, lighting, and beyond *(Invited Paper)*

Yajie Dong, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Quantum dots (QDs) have gone through a long journey before finding their ways into the display field. This talk will briefly touch on the history before trying to answer several key questions related to QDs applications in display: What are QDs? How are they made? What properties do they have and Why? How can these properties be used to improve color and efficiency of display, in either photoluminescence (PL) or electroluminescence (EL) mode? And what are the remaining challenges for QDs wide adoption in display industry? Lastly, some most recent progresses in our UCF lab at both PL and EL fronts will be highlighted. For PL, a cadmium-free perovskite-polymer composite films with exceptionally narrow emission green peaks (FWHM ~20 nm) and good water and thermal stability will be reported. Together with red quantum dots or PFS/KSF phosphors as down-converters for blue LEDs, a white-light source with 95% Rec. 2020 color gamut was demonstrated [1]. For EL, red quantum dot light emitting devices (QLEDs) with record luminance of 165,000 Cd/m2 has been obtained at a current density of 1000 mA/cm2 with a low driving voltage of 5.8 V and CIE coordinates of (0.69, 0.31). [2] The potential of using these QLEDs for light sources for integrated sensing platform [3] or high efficiency, high color quality hybrid white OLED [4] will be discussed.

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[3] J. He, H. Chen, S. T. Wu, and Y. J. Dong, Integrated Sensing Platform Based on Quantum Dot Light Emitting Diodes. SID Symp. Dig. Tech. Pap. 47, 344-346 (2016).

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10126-5, Session 1

Evaluation of display technologies for Internet of Things (IoT)

Julia Sabo, Tobias Fegert, Matthaeus Cisowski, Anatolij Marsal, Domenik Eichberger, Karlheinz Blankenbach, Pforzheim Univ. (Germany)

Internet of Things (IoT) is a booming industry. We investigated several (semi-) professional IoT devices in combination with reflective displays and LEDs. First, these displays were compared for reflectance and ambient light performance. Two measurement set-ups with diffuse conditions were used for simulating typical indoor lighting conditions of IoT displays. E-paper displays were evaluated best as they combine a relative high reflectance with large contrast ratio. Reflective monochrome LCDs show a lower reflectance but are widely available.

Second we studied IoT microprocessors (μP) interfaces to displays. A μP can drive single LEDs and Seg 8 LEDs directly by GPIOs. Other display technologies require display controllers with a parallel (GPIO) or serial (SPI, I?C) interface to the microprocessor as they need dedicated waveforms for driving the pixels. Most suitable are display modules with built-in display RAM as only pixel data have to be transferred which changes. A HDMI output (e.g. Raspberry Pi) results in high cost for the displays. So AMLCDs (TFTs) and AMOLEDs are not suitable for low to medium cost IoT systems.

We compared and evaluated furthermore status indicators, icons, text and graphics IoT display systems regarding human machine interface (HMI) characteristics and effectiveness as well as power consumption. We found out that low resolution graphics bistable e-paper displays are the most appropriate display technology for IoT systems as the show as well information after a power failure or power switch off during maintenance. LED indicators are the most cost effective approach which has however very limited HMI capabilities.

10126-6, Session 1

Dielectric breakdown of fast switching LCD shutters

Gatis Mozolevskis, EuroLCDs, SIA (Latvia); Edgars Nitiss, Univ. of Latvia (Latvia); Arturs Medvids, Riga Technical Univ. (Latvia)

Fast liquid crystal optical shutters due to fast switching, vibrationless control and optical properties have found various applications: replacement for mechanical shutters, 3D active shutter glasses, 3D volumetric displays and more. Switching speed depends not only on properties of liquid crystal, but also on applied electric field. Applied voltage can exceed >10 V/micron and dielectric breakdown can occur, thus dielectric thin film is needed between transparent conductive electrode to increase resistance to dielectric breakdown.

In this work we have compared electrical and optical properties of liquid crystal displays with dielectric thin films with thicknesses up to few hundred nanometers coated by flexoprinting method and magnetron sputtering. Dielectric breakdown values show flexographic coatings to have higher resistance to dielectric breakdown, although sputtered coatings show better optical properties. In this work dielectric breakdown mechanism will be discussed.

10126-27, Session 1

Design of ultra-low power consumption TFT-LCD-based eco-display *(Keynote Presentation)*

Han-Ping David Shieh, Fang Cheng Lin, Yi-Pai Huang, National Chiao Tung Univ. (Taiwan)

Color breakup is a lethal issue of a high light-efficiency field-sequential-color (FSC) LCD. Applying local color-backlight-dimming technology to a color filterless FSC-LCDs, we demonstrated “Stencil-FSC” methods with a field rate as low as 120Hz to render a high luminance “multi-color” image on a single-field and effectively suppress color breakup. For more efficiently suppress this color breakup issue, this paper further proposes the edge-Stencil-FSC method utilizing a global backlight controlling and can much reduce the computational complexity and make an FSC display more promising as next generation eco-displays.

10126-7, Session 2

Augmented-reality 3D-display based on integral imaging *(Invited Paper)*

Qiong-Hua Wang, Huan Deng, Han-Le Zhang, Sichuan Univ. (China); Min-Yang He, Sichuan Univ (China)

Integral imaging (II) is a good candidate for augmented reality (AR) display, since it provides various physiological depth cues so that viewers can freely change the accommodation and convergence between the virtual three-dimensional (3D) images and the real-world scene without feeling any visual discomfort. We propose three AR 3D display systems based on the theory of II. In the first AR system, a micro II display unit reconstructs a micro 3D image, and the mciro-3D image is magnified by a convex lens. The lateral and depth distortions of the magnified 3D image are analyzed and resolved by the pitch scaling and depth scaling processes. The magnified 3D image and real 3D scene are overlapped by using a half-mirror to realize AR 3D display. The second and third AR systems both use a holographic optical element (HOE) as an image combiner. The HOE is a volume holographic grating which functions as a micro-lens array for the Bragg-matched light, and as a transparent glass for Bragg mismatched light. In the second system, the HOE records the wavefronts of a set of tilted spherical waves, and the 3D image is reconstructed at an oblique viewing angle, which presents the floating 3D feature. In the third system, a reference beam can reproduce a virtual 3D image from one side and a reference beam with conjugated phase can reproduce the second 3D image from other side of the HOE, which presents double-sided 3D display feature.

10126-8, Session 2

Accommodation response measured by photorefractive accommodation measurement device

Byoung-Sub Song, Thibault Leportier, Min-Chul Park, Korea Institute of Science and Technology (Korea, Republic of)

Although accommodation response plays an important role in the human vision system for perception of distance, some three-dimensional (3D) displays offer depth stimuli regardless of the accommodation response. The consequence is that most observers watching 3D displays have complained about visual fatigue. The measurement of the accommodation response is therefore necessary to develop human-friendly 3D display. However, only few researches about accommodation measurement have been reported. Most researches have been focused on the measurement and analysis of monocular accommodation responses only because the accommodation response works individually in each eye. Moreover, a main eye perceive dominantly the object distance. However, the binocular accommodation response should be examined because both eyes are used to watch the 3D display naturally.

The photorefractive accommodometer that we developed enabled to measure changes in the accommodation response of the two eyes simultaneously. Two cameras acquired separately the infrared image reflected from each eyes after the reflected beams passed through a cylindrical lens. The changes in the accommodation response could then be estimated from the changes in the astigmatism ratio of the infrared images that were acquired in real time.

In this paper, we compared the accommodation responses of main eye between the monocular and the binocular conditions. The two eyes were measured one by one, with only one eye opened, during measurement for monocular condition. Then the two eyes were examined simultaneously for binocular condition. In the results, we observed similar tendencies for main eye accommodation response in both cases.

10126-9, Session 2

Effect of spatial coherence of LED sources on image resolution in holographic displays

Vahid Pourreza Ghoushchi, Koç Univ. (Turkey); Mehdi Aas, Univ. Twente (Netherlands); Erdem Ulusoy, Hakan Urey, Koç Univ. (Turkey)

Holographic Displays (HDs) provide 3D images with all natural depth cues via computer generated holograms (CGHs) implemented on spatial light modulators (SLMs). HDs are coherent light processing systems based on interference and diffraction, thus they generally use laser light. However, laser sources are relatively expensive, available only at some particular wavelengths and difficult to miniaturize. In addition, highly coherent nature of laser light makes some undesired visual effects quite evident, such as speckle noise, interference due to stray light or defects of optical components. On the other hand, LED sources are much cheaper, Available in variety of wavelengths, has small die size, and no speckle artifact. However, their finite spatial size introduce some degree of spatial incoherence in an HD system and degrade image resolution, which is the subject we study in this paper. Our theoretical analysis indicates that the amount of resolution loss depends on the distance between hologram and virtual object planes. For some special object distances, the source size has no effect at all. We also performed experiments with different configurations using lasers and LEDs with different emission areas that vary from 50 μm to 200 μm. Displaying the USAF target at different depths, we determined MTF curves which agree well with our theoretical model. The results show that it is possible to find configurations where LEDs combined with pinholes that preserve resolution in high spatial frequencies while keeping the loss in light efficiency within tolerable limits.

10126-10, Session 2

Application of the digital optical phase conjugation method for a three-dimensional polygonal hologram formation

Tatiana A. Vovk, Nikolay V. Petrov, ITMO Univ. (Russian Federation)

The problem of three-dimensional holographic imaging is relevant because of rapid digital technologies and imaging methods development. The studies of low-calculation 3D holographic imaging techniques seem to be promising due to the complexity of 3D digital holography approaches, including point-source summation and look up table techniques. Here we propose an investigation of digital optical phase conjugation (DOPC) method applicability and efficiency estimation for the problem of three-dimensional holographic imaging. The DOPC technique uses the numerical wavefront propagation from desired objects (point source is the simplest case) in order to get needed phase distributions in the registration plane. For imaging of several simple objects ensemble the random mix up of registration plane phase distribution can be used. Besides this, unnecessary diffraction orders will appear. We apply the method of angular spectrum of plane waves (AS) for the wavefront propagation, as it is accurate for the distances that appear in numerical simulation. We validate the basic properties of DOPC for the case of three-dimensional figure composed with two-dimensional polygons. We also compare DOPC method with numerical point-source summation imaging technique. We investigate the dependency of different elementary illuminators' (i.e. point sources) phase distributions on the method used for image formation. Since the simplicity of the DOPC method, this approach is useful for the fast basic 3D holographic image formation.

10126-11, Session 2

Viewing angle enhancement of a real-time integral imaging system using multi-directional projections and GPU parallel processing

MD. Ashraful Alam, BRAC Univ. (Bangladesh) and Chungbuk National Univ. (Korea, Republic of); MD. Sifatul Islam, Mohd. Zishan Tareque, Mahfuze Subhani Protik, M. Rashidur Rahman Rafi, BRAC Univ. (Bangladesh); Md. Shahinur Alam, Nam Kim, Chungbuk National Univ. (Korea, Republic of)

A novel method of viewing angle enhancement of a real-time integral imaging system using multi-directional projections and GPU parallel processing is proposed. The proposed system is composed of three processes: information acquisition of real objects, generation of multi-directional elemental image sets, and reconstruction of 3D images by using multi-directional projections scheme. To implement this system, depth and color (RGB) information of each object point are captured by a depth camera; then, a dynamic algorithm and GPU parallel processing are used for generating multi-directional elemental image sets to be illuminated in different directions as well as to maintain a real-time processing seed; and finally, 3D images are reconstructed by using a time-multiplexed multi-directional projection scheme through an appropriate optical setup of a projection-type integral image system. Multi-directional illuminations of elemental image sets enhance the optical ray divergence of reconstructed 3D images according to the directional projection angles. Hence, a real-time integral imaging system with enhanced viewing angle is achieved.

10126-12, Session 2

Optical experimental demonstration of the holographic display based on integral imaging pickup system

Nam Kim, Wei-Na Li, Chungbuk National Univ. (Korea, Republic of)

We propose a scheme to achieve a fast generation of the computer generated hologram (CGH). The CGH is generated from the integration of the holograms of a series of sub-layers including the points with the same depth. These points are transformed by a mapping relationship of a series of sub-images. The sub-images are converted from the elemental image array captured by the integral imaging pickup system. The proposed method is composed of five procedures: capturing the elemental images, mapping from the elemental image array to a point cloud, constructing a series of sub-layers based on the depth information, hologram generation, and hologram display. A mapping method was developed to achieve a point cloud from the elemental image array. It consists of several steps. Firstly, sub-images are converted from the captured elemental image array. Secondly, depth information for each sub-image is calculated using the optical flow method and constraints. Thirdly, the coordinate (x, y) pairs of the corresponding depth are also calculated. Therefore, a series of corresponding coordinates (x, y, z) are calculated from the elemental image array. It indicates that a point cloud is achieved through this mapping method. Subsequently, a series of sub-layers are constructed. Then a hologram is generated. Since the hologram is not generated from each point, instead of from each sub-layer including the points with the same depth, the generation speed of the CGH must be enhanced significantly. Eventually, a spatial light modulator (SLM) and a green laser beam are utilized to display this hologram of the original 3D object.

10126-13, Session 2

Augmented Reality 3D Display Using Head-Mounted Projectors and Transparent Retro-reflective Screen

Shoaib R. Soomro, Hakan Urey, Koç Univ. (Turkey)

A 3D augmented reality display is proposed that can provide glass-free stereo parallax using a highly transparent projection screen. The proposed display is based on a transparent retro-reflective screen and a pair of laser pico projectors placed close to the user's head. The retro-reflective screen directs incident light towards its source with little scattering so that each of the user's eyes only perceives the content projected by the associated projector. Each projector displays one of the two components (left or right image) of stereo content. The retro-reflective nature of screen provides high optical gain compared to the regular diffused screens. The partially patterned retro-reflective material on clear screen substrate introduces optical transparency and facilitates the user to see the real world scene on the other side of screen. The working principle and optical design of the proposed see-through 3D display are presented. A tabletop prototype consisting of an in-house fabricated 50x30 cm2 see-through retro-reflective screen and a pair of 30 lumen pico-projectors with custom 3D housing is demonstrated. Geometric calibration between projectors and optimal viewing conditions (display eyebox, eye-to-projector distance) are discussed. The display performance is evaluated by measuring the luminance and crosstalk for each eye. The screen provides high luminance (up to 200 cd/m2) while maintaining the 75% screen transparency. The crosstalk between left and right views is measured as <20% at the viewing distance of > 50 cm, which is within acceptable range.

10126-14, Session 3

Color control through FRET efficiency modulation using CDI

Karni Wolowelsky, Eric Guyes, Shimon Rubin, Matthew Suss, Moran Bercovici, Carmel Rotschild, Technion-Israel Institute of Technology (Israel)

Although much progress was made in light emitting devices, the ability to electrically control their spectral emission remains limited. We will present a novel approach and experimental results for dynamic color control, by electrically modulating the non-radiative Forster resonance energy transfer (FRET) efficiency between donor and acceptor dyes in a solution. FRET efficiency depends on the 6th power of the distance between donor and acceptor dye molecules, and thus, it is sensitive to variations in acceptor's concentration. Controlled acceptor concentrations could be achieved by attracting or repelling ionic dyes from the electrodes using a capacitive deionization (CDI) cell, with high surface area porous electrodes. This approach to dynamic color control may open new directions in 100% fill-factor displays, and can be expanded to energy saving applications such as controlling building's external wall emissivity.

We studied the modulation of a single dye emission using a CDI cell with negatively charged Fluorescein Sodium Salt in aquatic solution. Photoluminescence was measured along few charging-discharging CDI cycles and showed the ability to control extensive optical response through CDI.

We experimented with two types of FRET-pair dyes: a) anion-cation, where the acceptor and the donor ions are oppositely charged, and b) zwitterion and ion, where the donor is neutral. We found that electrical control on FRET in aquatic solution is weak, due to hydrophobic attractive interaction between the acceptor and the donor. In order to avoid this effect, we are experimenting FRET control in organic solvents. These results will be presented in the talk.

10126-15, Session 3

A large-scale NEMS light-emitting array based on CVD graphene

Hyungsik Kim, Young Duck Kim, Changhyuk Lee, Columbia Univ. (United States); Sunwoo Lee, Cornell Univ. (United States); Dong-jea Seo, Columbia Univ. (United States) and Yonsei Univ. (Korea, Republic of); Sahng-Kyoon Jerng, Seung-Hyun Chun, Sejong Univ. (Korea, Republic of); James Hone, Kenneth L. Shepard, Columbia Univ. (United States)

Graphene has received much interest from optical communities largely owing to its photon-like linear energy band structure called Dirac cone. While majority of the recent research has dealt with plasmon and polariton of the two-dimensional material, a recently reported graphene light emitter could render a new dimension of applications, particularly in high-speed optical communication. Moreover chemical vapor deposition (CVD) growth technique for graphene is available today providing means for scalable high quality graphene.

The reported graphene emitter provides broadband light emission from visible to mid-infrared which could be instrumental in multi-color display units and optical communications, however a truly large scale implementation has not previously been achieved. Here we demonstrate a CMOS-compatible 262,144 light-emitting pixels array (10 x 10 mm2) based on suspended CVD graphene nano-electro-mechanical systems (GNEMS). A single photoemission area is 19.6 μm2 and a unit pixel is consisting of 512 photoemission devices (16 x 16) where a multiplexer and a digital to analog converter (DAC) are used to control each pixel. This work clearly demonstrates scalability of multi-channel GNEMS light-emitting array, an atomically thin electro-optical module, and further paves a path for its commercial implementation transparent display or high-speed optical communication.

10126-16, Session 3

Speckle contrast reduction using an in-line fiber-optic diffuser

Ju Il Hwang, Seungmin Lee, Jong Cheol Shin, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

Laser sources for illumination of projection systems have been attracting much attention because of their many advantages, such as high image brightness, high optical efficiency, and wider color gamut. The main issue in the laser based projector, however, is the emergence of speckle patterns that severely degrade the quality of the image. In order to mitigate speckle, a number of the speckle reduction methods have been reported. Among these methods, as the most effective way, the angular decorrelation methods can simply suppress speckle pattern by using the mechanical vibration or rotation of a diffuser. However, a diffuser exploited in a laser based projector to suppress speckle patterns has transmission optical loss of ~20%, which is not desirable in aspect of optical efficiency.

An in-line fiber-optic diffuser is proposed and experimentally demonstrated to dramatically alleviate the speckle contrast ratio by inducing angular decorrelation of light. The proposed in-line fiber-optic diffuser is realized by randomly polishing a multimode fiber with versatile modal phases. The enormously high divergence angle of light illumination based on the proposed in-lie fiber-optic diffuser is effectively achieved. We investigate the effect of surface roughness of the randomly polished multimode fiber on the speckle contrast ratio, which is successfully suppressed to be ~4%.

10126-28, Session 3

Design of a 360-degree holographic 3D video display using commonly available display panels and a paraboloid mirror

Levent Onural, Bilkent University (Turkey)

Even barely acceptable quality holographic 3D video displays require hundreds of mega pixels with a pixel size in the order of a fraction of a micrometer, when conventonal flat panel SLM arrangement is used. Smaller pixel sizes are essential to get larger diffraction angles. Common flat display panels, however, have pixel sizes in the order of tens of micrometers, and this results in diffraction angles in the order of one degree. Here in this design, an array of commonly available (similar to high-end mobile phone display panels) flat display panels, is used. Each flat panel, as an element of the array, directs its outgoing low-dffraction angle light beam to corresponding small portion of a large size paraboloid mirror; the mirror then reflects the slowly-expanding, information carrying beam to direct it at a certain exit angle; this beam constitutes a portion of the final real ghost-like 3D holographic image. The collection of those components from all such flat display panels cover the entire 360-degrees and thus constitute the final real 3D table-top holographic display with a 360-degrees viewing angle. The size of the resultant display is smaller compared to the physical size of the paraboloid mirror, or the overall size of the display panel array; however, an acceptable size table top display can be easily constructed for living-room viewing. A matching camera can also be designed by reversing the optical paths and by replacing the flat display panels by flat wavefront capture devices.

Conference 10127: Practical Holography XXXI: Materials and Applications

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10127-1, Session 1

Effective public security features for embossed holograms *(Invited Paper)*

Stanislovas J. Zacharovas, Geola Digital uab (Lithuania); Ramunas Bakanas, Geola Digital uab (Lithuania) and Kaunas Univ. of Technology (Lithuania); Andrejs Bulanovs, Daugavpils Univ. (Latvia); Vadivelan Varadarajan, Ignetta Holographics (P) Ltd. (India)

Modern embossed hologram for security applications are mostly originated employing the following direct master-original writing techniques: E-beam, Dot-matrix, Image-matrix. Those techniques allow obtaining of quite sophisticated microscopic images containing complex optical security features, usually identified with optical aids. Some companies employ Digital H1 master recording and analogue H1-H2 transfer of said H1 master (DI-HO). This technique allows integrating some optical security features identified with optical aids. Few companies still employ pure analogue H1 master recording and analogue H1-H2 transfer, which, however could supply three-dimensional image on hologram, usually is providing only differently positioned images of 2D transparences.

So, all modern embossed holograms originating techniques, except DI-HO do not provide origination of deep three-dimensional image on embossed hologram. Any of those widely used techniques do not allow obtaining deep three-dimensional image AND sophisticated optical security features.

Thus we are proposing a solution - the combination of novel master-original writing technique one hologram. The proposed technique merges deep 3D holographic images with commonly used optical security features. Deep 3D images were recorded on photoresist with Geola's holographic printer containing their proprietary pulsed laser. Optical security features were then overexposed onto the photoresist plates containing latent images of deep 3D scenes. The photoresist plates with several exposures (containing optical security features and deep 3D images) were then developed. Embossed holograms, containing such effective public security features as full colour 3D images, guilloches, rainbow patterns and such optical security features as microtext and laser readable hidden image were manufactured.

10127-2, Session 1

Coherent backlight unit using holographic optical elements for full-color flat-panel Holographic Display

Sun Il Kim, Chil-Sung Choi, Jungkwuen An, Hoon Song, Yunhee Kim, Young Kim, Geeyoung Sung, Wontaek Seo, Juwon Seo, Yun-Tae Kim, Hojung Kim, Yongkyu Kim, Hong-Seok Lee, Sungwoo Hwang, Samsung Advanced Institute of Technology (Korea, Republic of)

We propose the coherent backlight unit (BLU) using Holographic Optical Element (HOE) for full color flat panel holographic display. This HOE BLU consists of two reflective type HOEs that change the optical beam path and shape by diffraction. The diverging incident beam is transformed to the collimated beam which has a very small diffraction angle (~5°) by HOE 1 (H1) in order to illuminate the whole display. And then this collimated beam is converged to a point at a distance from glass substrate by HOE 2 (H2). As a result, the diverging incident beam is converted to a point light by H1 and H2. If the high resolution Spatial Light Modulator that displays Computer Generated Hologram is illuminated by HOE BLU, then we can see the hologram image through a view point near focal point.

Practically, we fabricated the full color HOE BLU for 5.5" flat panel holographic display by using proposed design. To illuminate whole panel, we need a HOE which is larger than 5.5" size. So we recorded 150mm x 90mm size HOE on the 10mm thickness glass substrate. This HOE BLU exhibits a total efficiency of ~5% at Red (660nm), ~5% at Green (532nm), ~3% at Blue (460nm) using optimized recording conditions for each wavelength. Finally, we could see a bright full color hologram image.

We will present the design, fabrication technique of full color HOE BLU and the reconstructed hologram image.

10127-3, Session 1

Backside imaging of a microcontroller with common-path digital holography

Markus Finkeldey, Lena Göring, Falk Schellenberg, Nils C. Gerhardt, Chris?tof Paar, Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

The investigation of integrated circuits (ICs), such as microcontrollers (MCUs) and system on a chip (SoCs) devices is a topic with growing interests. The need for fast and non-destructive imaging methods is given by the increasing importance of hardware Trojans, reverse engineering and further security related analysis of integrated cryptographic devices. In the field of side-channel attacks, for instance, the precise spot for laser fault attacks is important and could be determined by using modern high resolution microscopy methods.

Digital holographic microscopy (DHM) is a promising technique to achieve high resolution phase images of surface structures. These phase images provide information about the change of the refractive index in the media and the topography. For enabling a high phase stability, we use the common-path geometry to create the interference pattern. The interference pattern, or hologram, is captured with a water cooled sCMOS camera. This provides a fast readout while maintaining a low level of noise. A challenge for these types of holograms is the interference of the reflected waves from the different interfaces inside the media. To distinguish between the phase signals from the buried layer and the surface reflection we use specific numeric filters.

For demonstrating the performance of our setup we show results with devices under test (DUT), using a 1064nm laser diode as light source. The DUTs are modern microcontrollers thinned to different levels of thickness of the Si-substrate. The effect of the numeric filter compared to unfiltered images is analyzed.

10127-4, Session 1

Digital holographic microtomography of fusion spliced optical fibers

Yating Deng, Feng Pan, Xichao Ma, Wen Xiao, BeiHang Univ. (China)

In this paper, we report three-dimensional (3D) measurement results of structural parameters of fusion spliced optical fibers using digital holographic microtomography. A holographic setup in microscopy configuration with the sample-fixed and setup-rotating scheme is established. A series of holograms is recorded from various incident angles. Then the filtered backprojection algorithm is applied to reconstruct the 3D refractive index (RI) distributions of the fusion spliced optical fibers inserted in the index-matching liquid. Experimental results exhibit the internal and external shapes of three kinds of fusion splices between different fibers, including a single-mode fiber (SMF) and a multimode fiber, an SMF and a panda polarization maintaining fiber (Panda PMF), and an SMF and a bow-tie polarization maintaining fiber (Bow-Tie PMF). With 3D maps of RI, it is intuitive to observe internal structural details of fused fibers and evaluate the splicing quality. This paper describes a powerful method for non-

invasive microscopic measurement of fiber splicing. Furthermore, it provides the possibility of detecting fiber splicing loss by 3D structures.

10127-5, Session 2

Holographic data visualization: using synthetic full-parallax holography to share information

Tove N. Dalenius, De Montfort Univ. (United Kingdom); Simon J. Rees, Univ. of Leeds (United Kingdom); Martin J. Richardson, De Montfort Univ. (United Kingdom)

This investigation explores representing information through data visualization using the medium holography. It is an exploration from the perspective of a creative practitioner deploying an interdisciplinary approach. The task of visualizing and making use of data and big data has been the focus of a large number of research projects during the opening of this century. As the amount of data that can be gathered has increased in a short time our ability to comprehend and get meaning out of the numbers has been brought into attention. This project is looking at the possibility of employing three-dimensional imaging using holography to visualize data and additional information.

To explore the viability of the concept this project has set out to transform the visualization of energy data calculations to a holographic medium. A Computational Fluid Dynamics (CFD) model of particle flow around a vehicle, and a model of Solar Irradiation energy mapped on an architectural structure were chosen to investigate the process. As no pre-existing software is available to directly transform the data into a compatible format the team worked collaboratory and trans-disciplinary in order to achieve an accurate conversion from the format of the visualization tool to a configuration suitable for synthetic holography production. The project also investigates ideas for layout and design suitable for holographic visualization of energy data. The study is structured in line with a Practice Based Research mode. Two completed holograms will be presented.

10127-6, Session 2

Sonorous images through digital holographic images

Maria Isabel Azevedo, ID+ Research Institute for Design, Media, and Culture, Univ. of Aveiro (Portugal); Elizabeth Sandford-Richardson, Univ. of the Arts London (United Kingdom)

The art of the last fifty years has significantly surrounded the presence of the body, the relationship between human and interactive technologies. Today in interactive art, there are not only representations that speak of the body but actions and behaviours that involve the body.

In holography, the image appears and disappears from the observer's vision field; because the holographic image is light, we can see multidimensional spaces, shapes and colours existing on the same time, presence and absence of the image on the holographic plate. And the image can be flowing in front of the plate that sometimes people try touching it with his hands.

That means, to the viewer will be interactive events, with no beginning or end that can be perceived in any direction, forward or backward, depending on the relative position and the time the viewer spends in front of the hologram. To explore that feature we are proposing an installation with four holograms, and several sources of different kind of sounds connected with each hologram. When viewers will move in front of each hologram they will activate different sources of sound. The search is not only about the images in the holograms, but also the looking for different types of sounds that this demand will require.

The digital holograms were produced using the HoloCam Portable Light System with the 35 mm camera Canon 700D to capture image information, it was then edited on computer using the Motion 5 and Final Cut Pro X programs.

10127-7, Session 2

Holographic Space: presence and absence in time

Yin-Ren Chang, Martin J. Richardson, De Montfort Univ. (United Kingdom)

In terms of contemporary art, time-based media generally refers to artworks that have duration as a dimension and unfold to the viewer over time that could be a video, slide, film, computer-based technologies or audio.

As part of this category, holography pushes this visual-oriented narrative a step further, which brings a real 3D image to invite and allow audiences revisiting the scene of the past, the moment of recording and space in time. Audiences could also experience the kinetic holographic aesthetics through constantly moving the viewing point or illumination source, which creates dynamic visual effects. In other words, when the audience and hologram remain still, the holographic image can only be perceived statically. This unique form of expression is not created by virtual simulation; the principal of wavefront reconstruction process made holographic art exceptional from other time-based media.

This project generates 3D printing technique to explore the nature of material aesthetics, transiting between material world and holographic space. In addition, this series of creations also reveals the unique temporal logic of hologram, presence and absence, an equivocal relationship existing in this media.

10127-8, Session 2

Light windows: a traveling exhibition dedicated to holography

Pedro M. Pombo, Emanuel Santos, Carolina L. Magalhães, Univ. de Aveiro (Portugal)

During 2015, the International Year of Light, a traveling exhibition was developed and dedicated to holography. Despite the holograms are present in our day life, through several formats and different applications, for general public these 3D images are strange elements from complex technology. This exhibition explores several contents related with holograms, such as history, techniques, equipments, setups and applications and it involves a main structure with six interactive exhibits and a lab for hologram recording. The exhibition includes a group of nine art holograms, a workshop table dedicated to scratch holograms and a touch screen with information about holography, which can be download on-site or at home. All these contents, based on hands-on activities, are organized into five areas: "see", "do", "explore", "holo kids" and "to know more". The holography lab is based on a portable Denisyuk system and it allows the public to notice the typical darkroom environment needed to work on holography and also it allows visitors to make holograms as a souvenir of the exhibition. There are two types of visits: "Exploring the world of holograms" focus on visiting all contents and "Let's make an hologram" that, besides visiting, allows also to make holograms. Light Windows is an exhibition dedicated to the general public that during the last year has been traveling around six Portuguese cities. This paper will present and analyze all results obtained and it will discuss exhibitions impact on visitors.

10127-9, Session 3

Mass production of volume holographic optical elements (vHOEs) using Bayfol(R) HX photopolymer film in a roll-to-roll copy process *(Invited Paper)*

Friedrich-Karl Bruder, Thomas Fäcke, Fabian Grote, Rainer Hagen, Dennis Hoenel, Eberhard Koch, Christian Rewitz, Guenther Walze, Brita Wewer, Covestro AG (Germany)

Volume Holographic Optical Elements (vHOEs) gained wide attention as optical combiners for the use in augmented and virtual reality (AR and VR, respectively) consumer electronics and automotive head-up display applications. The unique characteristics of these diffractive grating structures – being lightweight, thin and flat – make them perfectly suitable for use in integrated optical components like spectacle lenses and car windshields. While being transparent in off-Bragg condition, they provide full color capability and adjustable diffraction efficiency. The instant developing photopolymer film Bayfol® HX provides an ideal technology platform to optimize the performance of vHOEs in a wide range of applications.

Important for any commercialization are simple and robust mass manufacturing schemes. In this paper, we present an efficient and easy to control one-beam recording scheme to copy a so-called master vHOE in a step-and-repeat process. In this contact-copy scheme, Bayfol® HX film is laminated to a master stack before being exposed by a scanning laser line. Subsequently, the film is delaminated in a controlled fashion and bleached. We explain working principles of the one-beam copy concept and discuss the mechanical construction of the installed vHOE replication line. Moreover, we treat aspects like master design, effects of vibration, and suppression of noise gratings. Furthermore, digital vHOEs are introduced as master holograms. They enable new ways of optical design and paths to large scale vHOEs.

10127-10, Session 3

Holographic interferometric and correlation-based laser speckle metrology for 3D deformations in dentistry

Markus Dekiff, Björn Kemper, Elke Kröger, Cornelia Denz, Dieter Dirksen, Westfälische Wilhelms-Univ. Münster (Germany)

The mechanical behavior of dental restorations and hard tissue is often investigated numerically by finite element analysis. For validation and optimization of such simulations, a comparison with experimentally measured deformation data is essential. This requires highly sensitive 3D metrology. We explore and considerably extend Digital Holographic Interferometry (DHI) for this task implementing a multimodal approach.

Our experimental workstation synergistically combines DHI with Digital Speckle Photography (DSP) and photogrammetry. DHI and DSP are employed to determine microscopic deformations. The photogrammetric method, which is based on digital image correlation of a projected laser speckle pattern, is used to determine the macroscopic 3D shape and position of the object under investigation. Merging the data sets permits the precise location of the measured displacements on the 3D surface model of the object and allows a direct comparison of measured deformations with data from numerical simulations. Furthermore, an enhanced visualization of the deformations is achieved. As true multimodal techniques are employed simultaneously, the approach allows for fast measurements within a highly multifunctional system.

In order to demonstrate the feasibility of our system, two applications are demonstrated: the quantitative determination of (1) the deformation of a mandible model due to mechanical loading of an inserted dental implant and of (2) the deformation of a (dental) bridge model under mechanical loading. The results are compared with data from finite element analyses of the investigated applications.

10127-11, Session 3

Holonetwork: communicating science through holography

Pedro M. Pombo, Emanuel Santos, Carolina L. Magalhães, Univ. de Aveiro (Portugal)

Since 1997 a program dedicated to holography has been developed and implemented in Portugal. This program started with focus on schools and science education. The HoloNetwork was created and it has been spread at a National level, involving a group of thirty schools and hundreds of students and teachers. In 2009 this network started to work to achieve a new target, the general public. With this goal, a larger program was developed with focus on science and society and on science communication through holography. For the implementation of this new program, special holography outreach activities were built, dedicated to informal learning and seven Science Centers around Portugal were add into the HoloNetwork. During last years, we have been working on holography, based on two main branches, one dedicated to schools and with the aimed to promote physics teaching and to teach how to make holograms, and another dedicated to society and with the aimed to promote holography and to increase scientific literacy.

This paper would analyze the educational program, all holography outreach activities, exhibitions or events, all equipments, materials and setups used and it would present the holographic techniques explored with students or with the public.

Finally, the results obtained in this work would be present and explored, with focus on students impact and outcomes, taking into account the public engagement on holography and its effect into scientific culture and analyzing the quality of holograms made by students and by the general public.

10127-12, Session 3

Numerical analysis of Bragg regime polarization gratings by rigorous coupled-wave analysis

Xiao Xiang, Michael J. Escuti, North Carolina State Univ. (United States)

We report on the numerical analysis of Bragg polarization gratings (PGs), especially those formed with liquid crystals, and study their general diffraction properties by Rigorous Coupled-Wave Analysis (RCWA). Different from traditional Bragg (isotropic) gratings, Bragg PGs are verified to have high diffraction efficiency for large field of view, which is ideal for exit-pupil-expanders in waveguide-based head-mounted-displays, spectroscopy, and fiber-optic telecommunication systems. The RCWA approach allows for a rigorous and accurate solution without paraxial approximations to be obtained with much lower computational cost and time, as compared to finite-element, finite-difference, or analytical coupled-wave approaches. Therefore, it enables the study of the complete transmittance and reflectance behavior of Bragg PGs in the most computationally efficient way. Diffraction characteristics including angular response and polarization sensitivity are investigated. The spectral response and thickness dependence are also examined. Comparisons with measured efficiency curves and analytical predictions derived from anisotropic coupled-wave analysis show good agreement.

10127-13, Session 3

Changes in diffraction efficiency of gratings with high-fructose corn syrup by aging

Nildia Y. Mejias-Brizuela, Univ. Politécnica de Sinaloa (Mexico); Arturo Olivares-Pérez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

High fructose corn syrup (HFCS) has employed for preparation of holographic gratings photosensitized with potassium dichromated, for to analyze the behavior of diffraction efficiency to first order. The behavior of diffraction efficiency to first order was analyzed at time intervals different: 24, 48, 72 and 96 hours, because to the recorded gratings showed instability in 24 hours after of record. For this reason, we decided to study in the time the evolution of diffraction efficiency parameter for to determine the maximum modulation of material holographic (HFCS-dichromated). The study realized showed that after of 72 hours, the photosensitized material reaches its maximum modulation, with a diffraction efficiency to first order of 4 %.

10127-14, Session 3

Volume holographic recording in bis(2,6-difluoro-3-(1-hydropyrrol-1-yl)phenyl) titanocene-doped PMMA photopolymer

Ying Liu, Yifan Hong, Fenglan Fan, Jinliang Zang, Xiaodi Tan, Beijing Institute of Technology (China)

Holographic data storage has large storage capacity and high transfer rate, it becomes one of the next-generation information storage technologies. Bis(2,6-difluoro-3-(1-hydropyrrol-1-yl)phenyl)titanocene (IRG 784) is a good photoinitiator doped in photopolymer, poly(methyl methacrylate) ?PMMA?is an excellent choice to making photopolymer with thickness of millimeter range. The solubility of phenanthrenequinone in MMA is a little low, for IRG 784 is very high. In this paper, I use IRG 784 as photoinitiator doped in PMMA made a kind of photopolymer with thickness of millimeter range for holographic data storage. We studied the optical characteristics of IRG 784–doped PMMA photopolymer with different weight ratio of IRG 784 doped.

For the preparation of material, we use methyl methacrylate solution as the monomer, azo-bis-isobutyronitrile as the thermo-initiator. The samples with clear optical transmission is orangered. The wavelength of laser for recording and reconstructing we used was 532nm. In the recording process, recording waves interfered for 2 seconds with the cross angle of 60 degrees. After 2 seconds is the reconstruction process, the original reference wave reconstructed the grating for 0.6 seconds. These two processes cycled until the reaction ended. We set the polarization state of signal wave as s-polarization. Both s-polarization and p-polarization as reference wave we used to recording.

Through a series of experiments, we can conclude that the weight ratio of IRG 784 dissolved in MMA is significant to increase diffraction efficiency. Although the diffraction efficiency is lower than in traditional holography, our material can be used in polarization holography.

10127-15, Session 3

Holographic three-dimensional display based on digital hologram print in materials

Jicheng Liu, Hongyue Gao, Pan Liu, Zhiqiang Zheng, Qiuxiang Yao, Wen Zhou, Fan Xu, Yingjie Yu, Huadong Zheng, Zhenxiang Zeng, Shanghai Univ. (China)

We present our work on new holographic polymer thin films with diffraction efficiency of ~90%, which has been demonstrated to be suitable to be used as hologram print materials. We record digital holograms generated by computer in the films, and 3D images are reconstructed with good quality. The material is sensitive enough to light, therefore holograms can be recorded under low laser intensity, and it does not need post-processing after holographic illumination. In this paper, we will introduce property of the holographic polymer films and 3D reconstructions from analog holograms based on real objects and digital holograms printed in them. The holographic material with high diffraction efficiency has potential applications of static holographic three-dimensional display, hologram print and diffraction optical devices.

10127-16, Session 4

Blind digital holographic microscopy

Patrick N. Anderson, Florian Wiegandt, Daniel J. Treacher, David T. Lloyd, Univ. of Oxford (United Kingdom); Kevin O'Keeffe, Univ. of Oxford (United Kingdom) and Swansea Univ. (United Kingdom); Simon M. Hooker, Ian A. Walmsley, Univ. of Oxford (United Kingdom)

High-resolution coherent imaging via digital holographic microscopy (DHM) requires a reference field that is both well known and highly divergent. This can be impractical, especially when operating at extreme ultraviolet (XUV) and soft x-ray wavelengths where optical performance is poor and coherent sources are weak.

Here, we demonstrate an iterative reconstruction algorithm that overcomes these limitations by simultaneously extracting both unknown object and reference fields from a sequence of digital holograms - a technique that we will refer to as blind DHM. The sequence in question is recorded in an off-axis DHM geometry as the reference is tilted about its focus, and the overlap between successive reference positions is optimized to guarantee algorithm convergence, whilst maximizing the effective numerical aperture and preserving the magnification properties of conventional DHM. Despite being iterative, the algorithm shares little resemblance with those popularized by Fienup [1], and the blind DHM reconstruction is reduced to a several circular shifts and element-wise operations, making it efficient and trivial to parallelize.

Extensive numerical and experimental testing at visible wavelengths has shown that blind DHM achieves near diffraction-limited coherent imaging where conventional DHM fails. This includes cases where the reference field is severely distorted, slowly diverging, or both as is typical in the XUV. Our experimental efforts are currently focused on translating blind DHM into the XUV, where sub-100 nm spatial resolution and elemental absorption edges are readily accessible.

[1] J. R. Fienup, "Phase retrieval algorithms: a comparison," Appl. Opt. 21, 2758-2769 (1982).

10127-17, Session 4

Sparsity-based fast CGH generation using layer-based approach for 3D point cloud model

Hak Gu Kim, Hyunwook Jeong, Yong Man Ro, KAIST (Korea, Republic of)

Computer generated hologram (CGH) is becoming increasingly important for a 3-D display in various applications such as virtual reality. In the CGH, holographic fringe patterns are generated without optical systems by numerically calculating them on computer simulation systems. However, a heavy computational cost is required to calculate the complex amplitude of all points of 3D objects on a CGH plane.

Recently, to efficiently obtain the diffraction fields of 3D objects, various methods such as wavefront recording plane (WRP) based approaches and

layer-based approaches were proposed using Fresnel diffraction or angular spectrum. They accelerated the speed of CGH generation by employing fast Fourier transform (FFT). More improving the speed of CGH generation is still required in practice.

This paper proposes a new fast CGH generation based on the sparsity of CGH (i.e., complex amplitude distribution on the CGH plane) for 3D point cloud model. The aim of the proposed method is to significantly reduce computational complexity while maintaining holographic fringe patterns. To that end, we present a new layer-based approach for calculating the complex amplitude distribution on the CGH plane by using sparse FFT (SFFT). We observe the CGH of a layer is sparse. So, dominant CGH is rapidly generated from a small set of signals by SFFT in calculating the Fresnel diffraction.

Experimental results have shown that the proposed method is one order of magnitude faster than recently reported fast CGH generation.

10127-18, Session 4

Near-to-eye electroholography via guided-wave acousto-optics for augmented reality

Sundeep Jolly, Nickolaos Savidis, Bianca Datta, MIT Media Lab. (United States); Daniel Smalley, Brigham Young Univ. (United States); V. Michael Bove Jr., MIT Media Lab. (United States)

Near-to-eye holographic displays act to directly project wavefronts into a viewer's eye in order to recreate 3-D scenes for augmented or virtual reality applications. Recently, several solutions for near-to-eye electroholography have been proposed based on digital spatial light modulators in conjunction with supporting optics, such as holographic waveguides for light delivery; however, such schemes are limited by the inherent low space-bandwidth product available with current digital SLMs. In this paper, we depict a fully monolithic, integrated optical platform for transparent near-to-eye holographic display requiring no supporting optics. Our solution employs a guided-wave acousto-optic spatial light modulator implemented in lithium niobate in conjunction with an integrated Bragg-regime reflection volume hologram.

10127-19, Session 4

Graphics processing unit accelerated numerical model for collinear holographic data storage system

Yong Huang, Xiao Lin, Xiaodi Tan, Beijing Institute of Technology (China)

Collinear holographic data storage system is a promising candidate for next-generation storage technique. Numerical simulation plays a vital role in the process of revealing physical insight into the effectiveness of proposed methods and providing guidance for further system optimization. In this work, we demonstrated a GPU accelerated numerical model for image formation in collinear holographic data storage system. An average 125 times speedup with 99.8% accuracy was achieved with our accelerated model compared to conventional CPU based simulation. Applications of our model for collinear holographic data storage system such as wavelength drift compensation and noise study were demonstrated.

10127-20, Session 4

An analysis of printing conditions for wavefront overlapping printing

Yasuyuki Ichihashi, Kenji Yamamoto, Koki Wakunami, Ryutaro Oi, Makoto Okui, Takanori Senoh, National Institute of Information and Communications Technology (Japan)

We have developed wavefront printer for high definition holographic image reconstruction in NICT (National Institute of Information and Communications Technology). Wavefront is optically reproduced by CGH (Computer Generated Hologram) displayed on SLM (Spatial Light Modulator) and recorded on a recording film as a reflection-type volume hologram in our wavefront printer. Generally, a pixel count of practical hologram data is larger than one of a single SLM such as micro LCD (Liquid Crystal Display). So we divide the entire hologram into a set of sub-hologram data and record a set of sub-holograms on the recording film as a sub-hologram cell sequentially in tiling manner. Then, some problems are caused by tiled printing. One of problems is a phase discontinuity of wavefront. The other problem is visible cells and split lines. To realize the optimal cell size for the high quality 3D image, a wavefront overlapping printing is usually required.

We try to simulate the phase discontinuity of wavefront by adding a random initial phase to every sub-hologram cell. We calculate a CGH of point light source with random initial phase and generate reconstructed images by using Fresnel-Kirchhoff diffraction formula. We calculate standard deviations and averages of spatial frequency spectrums of the reconstructed images. As results, we can presume printing conditions such as the optimal cell size and overlapping conditions. We aim to generate the wavefront printed holograms and compare to simulated reconstructed images.

10127-21, Session 4

Computation of exact diffraction field from its distributed samples

Gokhan B. Esmer, Marmara Üniv. (Turkey)

Accurate calculation of diffraction field of a three dimensional object is an important problem in comuter generated holograms. Most of the algorithms used for diffraction field calculation in computer generated holography use superposition of diffraction fields emitted by each elementary building blocks of the three dimensional object. However, the possible mutual couplings between those diffraction fields are omitted, because each elementary building block assumed as a light source. The proposed diffraction field calculation algorithm pave the way to compute diffraction field of three dimensional objects from their distributed samples taken over the space.

Calculation of the exact diffraction field of a three dimensional object from its samples taken over the entire space can be obtained by defining it as an inverse problem. For that purpose, we assume that a diffraction field is defined on a reference plane, then a linear system that relates diffraction field at given samples and the diffraction field on the reference plane is set. To calculate the exact diffraction field from the given samples, we utilize a generalized simplex algorithm for L1-norm minimization. We assume that values of the diffraction field on the reference plane are real and nonnegative. Sparse representation can be obtained by estimating the diffraction field on the reference plane from the available samples. The proposed algorithm gives perfect reconstruction of the original diffraction field by using much fewer sample points taken over the space compared to an alternative algorithms based on L2-norm minimization.

10127-22, Session 5

Investigating numerical reconstruction quality and sparsity constraints on the holographic fringe pattern in digital holography

Hyunwook Jeong, Hak Gu Kim, Yong Man Ro, KAIST (Korea, Republic of)

In this paper, we investigate the quality factors of numerical reconstruction in digital holography that depends on the change of an original holographic data. In particular, we focus on the investigation of a small number of signals based on sparsity from a holographic fringe pattern and associated numerical reconstruction.

The sparsity of holographic fringe pattern plays a key role in reconstruction quality in compressive holography. Holographic fringe pattern generated by Fresnel diffraction is a complex amplitude distribution and sparse in frequency domain. Original 3D data can be estimated from a small set of the holograms.

In this paper we investigate how severely the sparsity constraints on holographic fringe pattern influence the overall quality of the numerically reconstructed data. A series of objective and subjective assessment experiments have been performed to investigate reconstruction qualities from computer-generated holograms (CGH). Numerical reconstruction of 3D images with various sparsity constraints on holographic patterns is performed to find proper sparsity of holographic fringe pattern for a satisfactory reconstruction quality. In addition, we investigate the reconstruction quality effect of various subsampling methods such as uniform sampling, random sampling, and magnitude-based sampling.

The experimental results have shown that reasonable reconstruction results are obtained with a sparse holographic fringe pattern (small number of signals, even twenty percent of original pattern). Furthermore, the results indicate that the way to extract the sparse pattern could significantly affects the quality of the numerical reconstruction in digital holography.

10127-23, Session 5

Off-axis self-interference incoherent digital holographic microscopy

Philjun Jeon, Heejung Lee, Byunghwy So, Wonsang Hwang, Yonsei Univ. (Korea, Republic of); Yoonsung Bae, ASAN Institute for Life Sciences, ASAN Medical Ctr. (Korea, Republic of); Dugyoung Kim, Yonsei Univ. (Korea, Republic of)

Three dimensional (3D) imaging is demanding technology required in fluorescence microscopy. Even though holography is a powerful method which can obtain 3D information of an object with a single-shot two-dimensional image, it could not be used easily in fluorescence microscopy because of the low coherence of fluorescence light. Lately, several incoherent holographic techniques such as scanning holography, Fresnel incoherent correlation holography (FINCH), and self-interference digital holography (SIDH) have been proposed. Major problems to be overcome in these methods are DC term removal, twin image ambiguity, and phase unwrapping. Off-axis holography is a straightforward solution which can solve these problems all at once. However, very short coherence length of fluorescence light makes it difficult to build an off-axis holography system to produce any interference pattern. A fluorescence protein which emits light centered at 600 nm with a 30 nm bandwidth has a coherence length as short as 20 ?m. In this paper we built an off-axis SIDH system for fluorescence imaging, and investigated various conditions and requirements for practical holographic fluorescence microscopy. Our system is based on a modified Michelson interferometer with a flat mirror at one arm and a curved mirror at the other arm of the interferometer. We made a phantom 3D fluorescence object made of 5 single-mode fibers coupled to a single red LED source to mimic 5 fluorescence point sources distributed by a few tens of micrometers apart. A cooled EM-CCD was used to take holograms of these fiber ends which emit only around 10 nW power.

10127-24, Session 5

An accurate algorithm to find the axial position of an object in lens-free inline digital holography

Hee-Jung Lee, Phil-jun Jeon, Junwoo Kim, Yonsei Univ. (Korea, Republic of); Yoon-sung Bae, Asan Medical Ctr. (Korea, Republic of); Dug-young Kim, Yonsei Univ. (Korea, Republic of)

Lens-free inline digital holographic microscopy (LIDHM) is a simple, robust, and cost-effective microscope system based on holography, which is made of a partially coherent point source such as a fiber coupled laser or a spectrally filtered broadband light source. Since it doesn't need any imaging lens or optical component, LIDHM can be easily applied to low-cost imaging, cytometry, telemedicine, and particle tracking. LIDHM is based on holography, and the depth information of a sample is calculated by a diffraction formula and a series of numerical processes such as numerical focusing with various autofocusing algorithms, frequency-domain filtering to remove twin images, etc. People put a sample very close to a detector array and very far from a point source in most lens-free imaging systems, and the light from a point source is assumed to be a plane wave between the sample and the detector array. This assumption is no longer true for an LIDHM system with high magnification, where the distance between the sample and the source is compatible to the distance between a sample and a detector array. Here we propose an accurate algorithm which can be used to calculate the actual position of a sample from the detector array. This is based on a diffraction formula for a hologram with a diverging reference wave from point source and a diffracted wave from a sample. We have experimentally demonstrated that depth information calculated by an autofocusing algorithm with a plane wave reference beam is off from the actual sample position.

10127-26, Session 5

Fast computer-generated hologram computation using rendered depth map image

Seyedmahdi M. K. Kazempourradi, Erdem Ulusoy, Hakan Urey, Koç Univ. (Turkey)

We propose a new method for computing realistic computer-generated holograms (CGHs) of three-dimensional (3D) objects, where we benefit from well-established graphical processing units (GPUs) and computer graphics techniques to handle occlusion, shading and parallax effects. The non-commercial Blender 3D software is used to render a 3D scene capture by a camera positioned at a given viewpoint.

The render provides a 2D perspective image including occlusion and shading effects. We also extract the depth map data of the scene. The intensity value and the position of the object is extracted by combining the rendered intensity image and the depth map image.

The normalized depth map image provides values between zero (the nearest object point) and 255 (the most far point). We divide the depth range into several planes and quantize the depth value of 3D image points to the nearest plane. In the CGH computation part, we perform proper Fresnel transformations of these planar objects and sum them up to create the part of the hologram corresponding to the particular viewpoint. We then repeat the entire procedure for all possible viewpoints and cover the hologram area. The experimental results show that the technique is capable of performing high quality reconstructions in a fast manner.

10127-27, Session PWed

Holographic recording mechanism in albumin films with iron ions

Jorge Ordóñez-Padilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Arturo Olivares-Pérez, Instituto Nacional de Astrofísica Óptica y Electrónica (Mexico); Omar Palillero-Sandoval, Universidad Autónoma del Estado de Morelos (Mexico)

Hypothesis of the changes in the formation of an image (hologram) through photo-physicochemical processes is proposed. For record the holographic grating: [albumin + iron ammonium citrate + hv], the photo-crosslinking through the transfer of electrons due to the mobility of ions and radicals in the system occurs. The polarity by charge transfer and the formation of free radicals among atoms and molecules occurs with application of laser He-Cd, ? = 442nm. The recorded generated from photochemical reactions, produces intramolecular bonds. The holographic grating thickness was 80?m, with diffraction efficiency of 15.5%.

10127-28, Session PWed

Angular multiplexing holograms of four images recorded on photopolymer films with recording-film-thickness-dependent holographic characteristics

Keiichi Osabe, Kotaro Kawai, Nagaoka Univ. of Technology (Japan)

Angular multiplexing hologram recording photopolymer films were experimentally studied. The films contained acrylamide as a monomer, eosin Y as a sensitizer, and triethanolamine as a promoter in a polyvinyl alcohol matrix. In order to determine the appropriate thickness of the photopolymer films for angular multiplexing, photopolymer films with a thickness of 29–503 ?m were exposed to two intersecting beams of a YVO laser at 532 nm to form a holographic grating with a spatial frequency of 653 line/mm.

The diffraction efficiencies as a function of the incident angle of reconstruction were measured. A narrow angular bandwidth and high diffraction efficiency are required for angular multiplexing; hence, we define the Q value, which is the diffraction efficiency divided by half the bandwidth. The Q value of the films depended on the thickness of the films, and was calculated based on the measured diffraction efficiencies. The Q value of the 297-?m-thick film was the highest of the all films. Therefore, the angular multiplexing experiments were conducted using 300-?m-thick films. In the angular multiplexing experiments, the object beam transmitted by a square aperture was focused by a Fourier transform lens and interfered with a reference beam.

The order of angular multiplexing was four. The signal intensity that corresponds to the squared-aperture transmission and the nose intensity that corresponds to transmission without the square aperture were measured. The signal intensities decreased with the order of angular multiplexing, and the noise intensities were not dependent on the order of angular multiplexing.

10127-29, Session PWed

C[upsilon]BE: Coherent [upsilon] Beam Educator

Vivian Amos Sureshkumar, M. Richardson, De Montfort Univ. (United Kingdom)

Today Holography has advanced rapidly due to technical melioration in the field of optics. Three-dimensional imaging has gained importance to upgrade the existing imaging and display system. Holography has become one of the branches of optics gaining significant importance with a vast number of technical and industrial applications. When we address holography the first thing that comes to mind is projecting a three dimensional object on thin air. The word holography has always been confused between peppers ghost effect. The famous English phrase “A picture is worth a thousand words”, means a complex idea can be conveyed by a single picture. The basic principle of holography sounds complex with all its technical terms.

This paper suggests a way to explain and summarise the principles of holography using C?BE: Coherent ? Beam Educator that contains a transmission hologram illuminated with a laser diode. This paper summarises the construction details of the C?BE and the optical setup to record the transmission hologram. It also briefs the circuit connections for the laser diode that’s works by a press button. When viewer presses the push button the original scene is reconstructed. It provides details regarding the angle of reference beam at recording and how the reference beam is compensated at reconstruction. The author also tries to explain the wavelength and angle shift of both recording and reconstruction source with mathematical equations. Also this paper highlights how the magnification of the recorded image varies with respect to the path length of the laser diode inside the box during reconstruction of the recorded hologram.

10127-30, Session PWed

Advanced channel modeling of holographic data storage considering degradation shapes of reconstructed image

Kyungchan Son, Sung-Yong Lim, Hyunseok Yang, Yonsei Univ. (Korea, Republic of)

Page-based holographic data storage (HDS) is very sensitive to disturbances such as tilt and media positioning because of extremely high density of HDS. As a result, reconstructed images are also affected by disturbances, which is represented as degradation of image and signal-to-noise ratio (SNR). Therefore, it is important to detect and compensate the disturbances of HDS. In order to detect and compensate the disturbances, there have been many researches using degradation shapes of reconstructed image. However, it is hard to obtain and analyze the degradation shapes because complex and iterative experiments are required. Furthermore, experiments also have to be done for applying detection and compensation algorithms. Because of inefficiency of experiments, channel model of HDS which can model degradation shapes with respect to disturbances is important. Channel model can reduce the number of experiment and improve efficiency of research. In previous research, channel model of holographic data storage was proposed, but detailed description of the mathematical model and degradation shapes with respect to disturbances direction and amplitude were not modeled.

In this paper, advanced channel model which is possible to model degradation shapes is proposed. Proposed channel model considers three causes which effect to media positioning and tilt: Bragg mismatch, imperfect phase conjugation, and media deformation due to temperature. In order to represent degradation of diffraction efficiency caused by Bragg mismatch and media deformation, k-sphere model whose vector concept is expanded to field to use in overall data page with each signal vectors revised by Rodrigues’ rotation formula is applied.

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10127-31, Session PWed

Lensless digital holographic microscope using in-line configuration and laser-diode illumination

Lena Göring, Markus Finkeldey, Adamou Adinda-Ougba, Nils C. Gerhardt, Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

In this paper we present a lensless transmission digital holographic microscope for the investigation of transparent samples. The setup consists of a laser diode, an object positioned on a cover slip and a CMOS sensor. We use a laser diode for illumination which emits a divergent beam and acts as a point source, so that additional components such as a pinhole are not required. The laser diode is operated below the lasing threshold to decrease the coherence length and thus to reduce speckle noise. Due to the compact and small size of the setup, it requires minimized effort for applications in field operation.

The lensless setup is characterized by using an USAF-target for determining the resolution and performance of the system. In the following, transparent or semitransparent samples are investigated. Microstructured plastic samples are placed on the specimen holder and characterized by the holographic microscope.

By applying the angular spectrum method on the recorded images, we are able to reconstruct the investigated objects. The in-line geometry of the setup facilitates the simplicity of the setup but also induces optical errors, for instance twin images. Twin images superimpose with the object's signal and require additional numerical reconstruction algorithms. For reducing the effect of the twin image problem, we apply an iterative phase retrieval algorithm. In the conclusion, we discuss the resolution and quality of the recorded images and evaluate the numerical reconstruction process.

10127-32, Session PWed

Effect of monomer diffusion on photoinduced shrinkage in photopolymer layers determined by electronic speckle pattern interferometry

Mohesh Moothanchery, Manojit Pramanik, Nanyang Technological Univ. (Singapore); Vincent Toal, Izabela Naydenova, Dublin Institute of Technology (Ireland)

The aim of this study is to determine the effects of monomer diffusion on shrinkage induced by holographic recording in photopolymer layers. Using phase shifting electronic speckle pattern interferometry the displacement at each pixel in the image of the object is measured by phase shifting technique so that a complete displacement profile of the object can be obtained. In order to study the effects of monomer diffusion on the displacement profile of photopolymer layers during holographic recording two sets of experiments were carried out. In the first set the exposure region was smaller than the photopolymer layer, allowing for the polymerisation driven monomer diffusion from unexposed to exposed area to take place. In the second set of experiments the exposed area is larger than the photopolymer layer, thus the effect of monomer diffusion is excluded. We have observed a reduction in shrinkage as an effect of diffusion of monomer molecules from the unexposed regions. This technique thus allows us to determine real time measurement on the effects of monomer diffusion during holographic recording.

10127-33, Session PWed

Compact holographic optical-element-based electronic speckle pattern interferometer for rotation and vibration measurements

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An out-of-plane sensitive electronic speckle pattern interferometer (ESPI) using holographic optical elements (HOEs) for studying rotation and vibration is presented. Phase stepping is implemented by modulating the wavelength of the laser diode in a path-length imbalanced interferometer. The time average ESPI method is used for vibration measurements. The factors influencing the measurement accuracy are reported. Some advantages and limitations of the presented system are discussed

10127-34, Session PWed

Full-color high-definition CGH reconstructing hybrid scenes of physical and virtual objects

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Computer holography has been steadily developed for the last decade. As a result, high-definition computer-generated holograms (CGHs) composed of several billion or ten billion pixels are produced and reported. These high-definition CGHs reconstruct high-quality 3D images comparable to that in conventional optical holography. However, it was very difficult to reconstruct full-color images by these high-definition CGHs, because three CGHs were needed to produce full-color images. Besides, complicated, expensive and nonportable optical system was also required in order to combine three primary color images.

Recently, we reported a novel technique for high-definition full-color CGHs with a color-filter used for liquid-crystal panels. This technique allows us to produce full-color CGHs composed of a single plate and place them on exhibition. To realize this type of full-color CGHs, we need a simulation technique to predict reconstruction as well as fabrication techniques.

In this paper, we present the simulation technique based on physical optics for designing the properties of the color filter in addition to the fabrication technique. Furthermore, we demonstrate full-color CGHs that reconstruct hybrid scenes comprised of physical real-existing objects and CG-model virtual objects. Here, the wave field of the physical object are obtained from dense multi-viewpoint images by employing the ray-sampling (RS) plane technique. As far as we know, full-color optical reconstruction of real views obtained from high-density RS planes has never been reported.

10127-35, Session PWed

Comparison of computation time and image quality between full-parallax 4G-pixels CGHs calculated by the point cloud and polygon-based method

Noriaki Nakatsuji, Kyoji Matsushima, Kansai Univ. (Japan)

Full-parallax high-definition CGHs composed of billions or sometimes ten billion pixels were created by using the polygon-based method. This was because the point cloud was generally too time-consuming to calculate this kind of full-parallax high-definition CGHs. Computation by the polygon-based method is most likely faster than that by the technique of point cloud. Recently, however, GPUs allow us to generate CGHs by point cloud much faster. The performance of GPU is also improving year by year. In addition, the reconstructed surfaces look noisy in the polygon-based method because it uses random phase in order to diffuse light emitted by a polygonal surface. Therefore, there is a great interest in a comparison of computation time and image quality between the polygon-based method and point cloud. However, point cloud and polygon-based method are very different in the principle, and thus, these have different types of parameters. Therefore, it is difficult to compare these two methods fairly.

In this paper, we adopt the parameter based human vision and measure computation time of object fields for full-parallax CGHs with 4 billion pixels, which reconstruct the same 3D scene, by using the point cloud with GPU and the polygon-based method with CPU. Additionally, we actually fabricate these CGHs and compare the optical reconstruction to verify the image quality.

10127-36, Session PWed

Holographic gratings with cupric chloride, PVA and organic dye

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Preliminary results of holographic diffraction gratings recorded in a matrix coated whit emulsion composed of cupric chloride, PVA and natural dye extracted pitahaya (Hylocereus undatus). A measure and characterization of concentrations of dye, with the diffraction efficiency was made.

10127-37, Session PWed

Albumin holograms with gentian violet dye

Arturo Olivares-Pérez, Valentín Dorantes García, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Mauricio Ortiz-Gutiérrez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); Santa Toxqui-López, Benemérita Univ. Autónoma de Puebla (Mexico); Manuel J. Ordoñez-Padilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Nildia Y. Mejias-Brizuela, Univ. Politécnica de Sinaloa (Mexico)

Transmission holograms, with egg albumin, were used as matrix, mixing the violet of gentian dye with ammonium dichromate, good holograms were obtained. Holograms were recorded at line 442 nm of laser He-Cd. It is describes the behavior of the diffraction efficiency based the parameters of energy and thickness.

10127-38, Session PWed

Nopal cactus film

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Nopal mucilage potentially has certain properties required for the preparation biofilms which can be used holographic replication recording medium. In this study mucilage from nopal was extracted and characterized by its ability to form films under different concentration. The transmission holographic diffraction gratings (master) were replicated into nopal catus films. The results showed good diffraction efficiencies. Mucilage from nopal could represent a good option for the development of films to replication holographic, owing to; it's low cost and its compatibility with the environmental.

10127-39, Session PWed

Recording of digital holograms of 3D-scenes with depth up to 0.5 meter

Pavel A. Cheremkhin, Nikolay N. Evtikhiev, Vitaly V. Krasnov, Mikhail N. Kulakov, Ekaterina A. Kurbatova, Vladislav G. Rodin, National Research Nuclear Univ. MEPhI (Russian Federation)

Digital holography allows to reconstruct information about objects and 3D-scenes, their amplitude and phase distributions. Currently it is widely used in different areas of science and technology: physics and astronomy, medicine, biology, chemistry, and etc. Digital holographic registration is obtained by shooting of the images of interference patterns created by object and reference beams. Reconstruction of the information can be performed numerically (using computer modeling of propagation of illumination) or optically (by displaying hologram on spatial light modulator and their lighting by coherent beam).

In this work scientific digital camera Megaplus II ES11000 was used for digital holograms recording. The camera has 4008 x 2672 pixels with sizes of 9 um x 9 um. For objects illumination, 50 mW frequency-doubled Nd:YAG laser with wavelength 532 nm was used.

Using the constructed setup, a number of digital holograms was recorded. Setup allows to record holograms in “transmission” and “reflection” modes of object's illumination. 3D-scenes depth were ranged from 1 mm to 0.5 m. Distances between elements of 3D-scene and digital camera's photosensor plane were equal to 0.7-1.4 m. Quantity of hologram's pixels was up to 2048 x 2048. 3D-scenes consisted of reflective objects (for example, coins) and transmissive ones (for example, contour images with static diffuser). Results of numerical reconstruction of sections of registered 3D-scenes are presented.

10127-40, Session PWed

Analysis of security of optical encryption with spatially incoherent illumination technique

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Applications of optical methods for encryption purposes have been attracting interest of researchers for decades. The first and the most popular is double random phase encoding (DRPE) technique. There are many optical

encryption techniques based on DRPE. Main advantage of DRPE based techniques is high security due to transformation of spectrum of image to be encrypted into white spectrum via use of first phase random mask which allows for encrypted images with white spectra. Downsides are necessity of using holographic registration scheme in order to register not only light intensity distribution but also its phase distribution, and speckle noise occurring due to coherent illumination. Elimination of these disadvantages is possible via usage of incoherent illumination instead of coherent one. In this case, phase registration no longer matters, which means that there is no need for holographic setup, and speckle noise is gone. This technique does not have drawbacks inherent to coherent methods, however, as only light intensity distribution is considered, mean value of image to be encrypted is always above zero which leads to intensive zero spatial frequency peak in image spectrum. Consequently, in case of spatially incoherent illumination, image spectrum, as well as encryption key spectrum, cannot be white. This might be used to crack encryption system. If encryption key is very sparse, encrypted image might contain parts or even whole unhidden original image. Therefore, in this paper analysis of security of optical encryption with spatially incoherent illumination depending on encryption key size and density is conducted.

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10128-1, Session 1

Integrated microwave photonics: a key enabling technology for radio-over-fiber *(Invited Paper)*

Stavros Iezekiel, Univ. of Cyprus (Cyprus)

We review recent progress in the development of photonic devices and integration, with the emphasis on potential applications in microwave photonics where size, weight and power consumption reduction will be crucial to the realisation of radio-over-fiber. Different material platforms such as InP, silicon photonics, silicon nitride will be compared for their suitability for active and passive component integration. Case studies in applications such as photonic beam forming will be used to illustrate the potential of integrated microwave photonics.

10128-2, Session 2

FireFly: reconfigurable optical wireless networking data centers *(Invited Paper)*

Mohsen Kavehrad, The Pennsylvania State Univ. (United States)

Data centers (DCs) are a critical piece of today's networked applications in both private and public sectors. The key factors that have driven this trend are economies of scale, reduced management costs, better utilization of hardware via statistical multiplexing, and the ability to elastically scale applications in response to changing workload patterns. A robust datacenter network fabric is fundamental to the success of DCs and to ensure that the network does not become a bottleneck for high-performance applications. In this context, DC network design must satisfy several goals: high performance (e.g., high throughput and low latency), low equipment and management cost, robustness to dynamic traffic patterns, incremental expandability to add new servers or racks, and other practical concerns such as cabling complexity, and power and cooling costs. Current DC network architectures do not seem to provide a satisfactory solution, with respect to the above requirements. In particular, traditional static (wired) networks are either:

(i) Overprovisioned to account for worst-case traffic patterns, and thus incur high cost (e.g., fat-trees or Clos), or

(ii) Oversubscribed (e.g., simple trees or leaf-spine architectures) which incur low cost but offer poor performance due to congested links. Recent works have tried to overcome the above limitations by augmenting a static (wired) "core" with some flexible links (RF-wireless or optical). These augmented architectures show promise, but offer only incremental improvement in performance. Specifically, RF-wireless based augmented solutions also offer only limited performance improvement, due to inherent interference and range constraints of RF links. Optical solutions offer high-bandwidth links and low latency, but have limited scalability, offer only limited flexibility (e.g., bipartite-matchings between the racks), and have a single point of failure. Furthermore, all the above architectures incur high cabling cost and complexity.

A robust datacenter network is fundamental to the success of critical and high performance networked applications today. Designing a datacenter network is challenging as it must simultaneously satisfy several goals: high-throughput and low latency, low equipment and management cost, robustness to dynamic traffic patterns, incremental expandability, and other practical concerns such as cabling complexity, energy footprint, and cooling costs.

In this context, traditional static network designs offer undesirable cost-performance tradeoffs: simple tree or leaf-spine designs incur less cost but provide poor performance, while high-performance Closnetwork or FatTree-like solutions are expensive as they are overprovisioned to account for worst-case traffic patterns. Recent work suggests augmenting these static networks with a few flexible (wireless or optical) links. However, these solutions offer incremental improvements and suffer from other limitations. Furthermore, all above architectures induce high cabling complexity, which increases cooling and energy costs.

This paper explores an alternative design point—a fully flexible and all-wireless datacenter inter-rack network based on free-space optical (FSO) links. We call this FireFly as in; Free-space optical Inter-Rack nEtwork with high FLexibilitY.

The Switch on top of a rack is a burst switch, as in TDAM burst switches in satellite communications. Packets are buffered to up to thousands of packets length to form a burst. The collimated laser beam, transmitted from the fiber collimator of FSO terminal, passes onto the gimbal-less two-axis MEMs micro-mirror of 2 mm diameter, which steers the beam ultrafast within large optical deflection of 10 degrees over the entire device bandwidth of 1.2 kHz. The MEMs mirror deflects it into the wide-angle lens that magnifies the optical scan-angles of the system by approximately 3X. This magnification is linear, resulting in overall scan capability of over 30°FoV. Power consumption of less than 1mW is several orders of magnitude lower than that of galvanometer mirrors. Outgoing FSO beam from MEMs beam steering mechanism passes auto-points onto a receive aperture and gets efficiently coupled into a fiber collimator. This fast and precise MEMs steering mechanism can switch the FSO from one rack to the next for reconfigurable networking, and enables auto-correction mechanism to correct any misalignment in real-time.

This vision, if realized, will offer unprecedented qualitative and quantitative benefits over state-of-the-art solutions:

(1) A flexible network can provide performance comparable to overprovisioned solutions with less infrastructure cost by adapting the topology to the prevailing traffic patterns;

(2) It eliminates cabling complexity, and cooling and power overheads;

(3) It acts as an enabler for datacenter operators to consider experimental topology designs that would otherwise be unrealizable; and

(4) It can take us closer to the vision of an energy-proportional datacenter by allowing operators to selectively enable links.

There are several fundamental challenges that need to be addressed to make this vision practical:

(i) Design of practical high-throughput FSO links for data centers that are reconfigurable with low latencies;

(ii) Algorithmic foundations for designing flexible topologies; and

(iii) Scalable network management mechanisms to guarantee correctness and performance.

We will discuss these issues in an oral presentation.

Collaborators Team:

• Penn State Univ.: Prof. Mohsen Kavehrad, Dr. Peng Deng, Dr. Yan Lou

• Stony Brook Univ.: Prof. Samir Das, Prof. Himanshu Gupta, Prof. Jon Longtin

• CMU: Prof. Vyas Sekar

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10128-3, Session 4

MEMS-based beam-steerable free-space optical communication link for reconfigurable wireless data center

Peng Deng, Mohsen Kavehrad, Yan Lou, The Pennsylvania State Univ. (United States)

Flexible wireless datacenter networks based on free space optical communication (FSO) links are being considered as promising solutions to meet the future datacenter demands of high throughput, robustness to dynamic traffic patterns, cabling complexity and energy efficiency. Robust and precise steerable FSO links over dynamic traffic play a key role in the reconfigurable optical wireless datacenter inter-rack network. In this work, we propose and demonstrate a reconfigurable bidirectional 10 Gbps FSO system incorporated with smart beam acquisition and tracking mechanism based on gimbal-less two-axis MEMS micro-mirror and retro-reflective film marked aperture. The fast MEMS-based beam acquisition switches laser beam of FSO terminal from one rack to the next for reconfigurable networks, and the precise beam tracking makes FSO device auto-correct the misalignment in real-time. We evaluate the optical power loss and bit error rate performance of steerable FSO links at various distances in X-Y-Z directions. Experimental results suggest that the MEMS based beam steerable FSO links hold considerable promise for the future reconfigurable wireless datacenter networks.

10128-4, Session 5

Radio over optical waveguide system-on-wafer for massive delivery capacity 5G MIMO access networks *(Invited Paper)*

Le Binh, Huawei Technologies Duesseldorf GmbH (Germany)

Delivering maximum information capacity over MIMO antennae systems beam steering is critical so as to achieve the flexibility via beam steering, maximizing the number of users or community of users in Gb/s rate per user over distributed cloud-based optical-wireless access networks. This paper gives an overview of (i) demands of optical –wireless delivery with high flexibility, especially the beam steering of multi-Tbps information channels to information hungry community of users via virtualized beam steering MIMO antenna systems at the free-license mmW region. (ii) Proposing a novel photonic planar integrated waveguide systems composing several passive and active, passive and amplification photonic devices so as to generate mmW carrier and embedded baseband information channels to feed to antenna elements. (iii) Integration techniques to generate a radio over optical waveguide (RoOW) system-on-wafer (SoW) comprising MIMO planar antenna elements and associate photonic integrated circuits for both up- and down- links. (iv) Challenges encountered in the implementation of the SoW in both wireless and photonic domains; (v) Photonic modulation techniques to achieve maximum transmission capacity per wavelength per MIMO antenna system. (vi) A view on control-feedback systems for fast and accurate generation of phase pattern for MIMO beam steering via a bank of optical phase modulators to mmW carrier phases and their preservation in the converted mmW domain . (vi) The overall operational principles of the novel techniques and technologies based on the coherent mixing of two lightwave channels

The entire SoW can be implemented on SOI Si-photonic technology or via hybrid integration. These technological developments and their pros- and cons- will be discussed.

10128-5, Session 5

High-responsivity 100GHz waveguide UTC-photodetector

Toshimasa Umezawa, Kouichi Akahane, Atsushi Matsumoto, Atsushi Kanno, Naokatsu Yamamoto, National Institute of Information and Communications Technology (Japan); Tetsuya Kawanishi, Waseda Univ. (Japan) and National Institute of Information and Communications Technology (Japan)

A high-speed and high sensitive analog photoreceiver is one of the key components of radio over fiber technology. In the advanced small-cell systems, low optical input power to a photoreceiver in remote antenna units (RAUs) would be speculated due to the many optical braches between a central base station and the RAUs. In our previous works, we have studied a W-band (90-110GHz) high speed photodetector using back-illuminated structure, which exhibited the wide 3dB bandwidth (f3dB) over 110 GHz, and the good flatness within ±1dB. However, the responsivity would be limited as low as 0.19A/W at 1550nm, due to the device structure.

In this report, we present a double cladding high-mesa type waveguide UTC photodetector in order to improve the responsivity. In the device structure, an InGaAs thin core layer was sandwiched by p-InP/InGaAsP and n-InP/InGaAsP cladding layers including a UTC structure, in order to make good optical coupling between the waveguide and fiber. Compared the mode field with single cladding layer structure, it was confirmed that a vertical mode field was enlarged. Without a spot size converter, the measured responsivity could be successfully obtained as high as 0.6 A/W at 1550nm, which suggested three time higher responsivity than back-illuminated structure, and higher responsivity than that in previous reports. The high frequency performance (f3dB =100GHz) could be also recognized. The device structure including the layer, doping level conditions and optical fiber coupling results would be discussed, and the performance would be characterized in detail.

10128-6, Session 5

Millimeter- and terahertz-wave over fiber technologies for high-speed communication and non-telecom applications *(Invited Paper)*

Atsushi Kanno, National Institute of Information and Communications Technology (Japan)

Demands for high-speed wireless communication have been accelerating the development of high-frequency millimeter- and terahertz-wave technologies. 100-Gb/s wireless communication will be demanded in high-frequency millimeter- and terahertz-wave bands in next 10 years; the high-capacity wireless communication is applicable for wireless mobile backhaul and fronthaul links connected between base stations for 5G mobiles. In the scenario, optical-fiber connectivity seamlessly to the wireless network is a key for reduction of the cost as well as complexity. A radio over fiber (RoF) technique meets the demands for seamless convergence between the optical and high-speed radio communication technologies. The RoF technique is also useful for high-frequency signal delivery over the fiber network from a centralized station to remote sites owing to the low loss of the optical fiber of 0.2 dB/km. RoF-network-connected millimeter- and terahertz-wave imaging system including a radar system is useful for intruder and foreign object debris detection in important facilities.

In the paper, we propose and demonstrate millimeter- and terahertz-wave wireless communication system directly connected to the RoF network. 100-GHz- and 300-GHz-band signal transmission generated by the optical modulation is successfully demonstrated with the data rates larger than 20 Gb/s in each band. Millimeter-wave distributed radar system is also discussed with a range resolution less than 10 cm for surveillance are of

500 x 100 m, which is designed for a foreign object debris detection system in the airport runway with target debris size of 1-inch height and 1-inch diameter metal pillar.

10128-7, Session 5

Array-antenna-electrode electro-optic modulators for millimeter-wave radio-over-fiber systems

Hiroshi Murata, Toshiyuki Inoue, Yuuki Matsukawa, Hironori Aya, Takashi Ikeda, Yasuyuki Okamura, Osaka Univ. (Japan)

Millimeter-wave (MMW) wireless technology is promising for fifth generation (5G) mobile communication systems owing to its outstanding characteristics for massive data transfer and connection capability by use of multiplexing techniques in frequency and spatial domains. MMW is also important for high-resolution radar, remote sensing, and imaging systems. Therefore, studies in MMW devices and sub-systems have recently been attracting much interest.

In order to construct MMW wireless communication systems, radio-over-fiber (RoF) technology is attractive, since it enables us to transfer or relay MMW signals with low loss and negligible crosstalk by use of a silica optical fiber with extremely low-propagation-loss. A MMW signal control in a photonic domain is also important for reducing latency in high-speed signal processing systems using analogue-to-digital converters and digital signal processors. Key devices and components for microwave/MMW RoF links have been developed since the proposal of the RoF concept. However, a signal converter from MMW to lightwave (LW) signals still remains challenging.

We have proposed new MMW-LW signal converters using array-antenna-electrode electro-optic (EO) $LiNbO_3$ modulators. In particular, by introducing polarization-reversed structures in the $LiNbO_3$ crystal/film of the device substrate, the conversion from wireless MMW signals to optical signals, and also the advanced functions of discrimination between space-division-multiplexed (SDM) wireless signals and generation of optical single-sideband (SSB) modulation signals are obtainable simultaneously.

In the presentation, newly-developed EO modulators operating in the 60 GHz band are discussed. Applications to up-links in 5G mobile communication systems are also presented.

10128-8, Session 6

Enabling technologies for millimeter-wave radio-over-fiber systems in next generation heterogeneous mobile access networks *(Invited Paper)*

Junwen Zhang, Georgia Institute of Technology (United States); Jianjun Yu, ZTE(Tx) Inc. (United States) and Georgia Institute of Technology (United States); Jing Wang, Mu Xu, Lin Cheng, Feng Lu, Shuyi Shen, Yan Yan, Hyunwoo Cho, Daniel Guidotti, Gee-kung Chang, Georgia Institute of Technology (United States)

Fifth-generation (5G) wireless access network promises to support higher access data rate with more than 1,000 times capacity with respect to current long-term evolution (LTE) systems. New radio-access-technologies (RATs) based on higher carrier frequencies to millimeter-wave (MMW) radio-over-fiber, and carrier-aggregation (CA) using multi-band resources are intensively studied to support the high data rate access and effectively use of frequency resources in heterogeneous mobile network (Het-Net). In this paper, we investigate several enabling technologies for MMW RoF systems in 5G Het-Net. Efficient mobile fronthaul/backhaul (MFH/MBH) solutions for 5G centralized radio access network (C-RAN) and beyond are proposed, analyzed and experimentally demonstrated based on both digital and analog schemes. Digital predistortion based on memory polynomial for analog MFH linearization are presented with improved EVM performances and receiver sensitivity. A novel digital MFH based on Delta-sigma modulation are also reported here with more than 4-times capacity improvement compared with legacy common public radio interface. We also propose and experimentally demonstrate a novel inter-/intra- RAT CA scheme for 5G Het-Net. The real-time standard 4G-LTE signal is carrier-aggregated with three broadband 60GHz MMW signals based on proposed optical-domain band-mapping method. RATs based on new waveforms have also been studied here to achieve higher spectral-efficiency (SE) in asynchronous environments. Full-duplex asynchronous quasi-gapless carrier-aggregation scheme for MMW ROF inter-/intra-RAT based on the FBMC, UFMC and filtered-OFDM are also presented with 4G-LTE signals. Compared with OFDM-based signals with large guard-bands, FBMC/UFMC achieves higher spectral-efficiency with better EVM performance at less received power and smaller guard-bands.

10128-9, Session 6

Coexistence and transmission of multiple radios over seamless fiber-wireless systems *(Invited Paper)*

Pham Tien Dat, Atsushi Kanno, Naokatsu Yamamoto, National Institute of Information and Communications Technology (Japan); Tetsuya Kawanishi, Waseda Univ. (Japan)

The coexistence of multiple radios, including multiple radio access technologies (RATs), services, operators, and signal components are considered important solutions for high-speed and heterogeneous communications and management in 5G and beyond networks. A new RAT in the millimeter-wave (MMW) band can provide very high throughput services to users. Legacy services such as 4G LTE-A or Wi-Fi signals can provide communications to other users and/or to distribute control data. Very low latency communications using single carrier signals can also be deployed to support delay sensitive applications such as vehicle-to-vehicle communications. Simultaneous transmission of multiple radios over the same fronthaul system is of particular importance to reduce the cost, power consumption, network complexity, and to support the fast deployment of new services. In this paper, we present flexible and efficient simultaneous transmission of multiple radios over a seamless fiber-wireless system. At central stations, a data-mapping algorithm can map different signals, including signal components in one RAT or signals from different RATs, onto the same optical transport channel. At remote cells, the signals can be received, down-converted, digitized, and de-mapped to recover transmitted radio signals. We present different transmission methods, including direct MMW radio signals over fiber, intermediate frequency over fiber with electrical up-conversion at remote cells, and radio over fiber system using optical up-conversion at remote cells for the simultaneous transmission of multiple radios at different frequency bands. We compare effects of fiber dispersion and nonlinear distortion on the signal transmission performance.

10128-10, Session 6

802.11ac WLAN MIMO radio-over-fiber distributed antenna system for in-building networks based on multicore fiber

Maria Morant, Roberto Llorente Sáez, Univ. Politècnica de València (Spain)

In this work we propose and evaluate experimentally the performance of IEEE 802.11ac WLAN standard signals in radio-over-fiber (RoF) distributed antenna systems based on multi-core fiber (MCF) for in-building WLAN connectivity. The RoF performance of WLAN signals with different

bandwidths is investigated up to the IEEE 802.11ac maximum of 160 MHz per user. We evaluate experimentally the performance of WLAN signals employing different modulation and coding schemes (MCS) achieving bitrates from 162 Mbps to 2340 Mbps per user in distances up to 300 m of a 4-core MCF.

The performance of the wireless standard multiple-input multiple-output (MIMO) processing algorithms included in WLAN signals applied to the RoF transmission in MCF optical systems is also evaluated. We measured the error vector magnitude (EVM) and the OFDM data burst information of the received WLAN signals after RoF transmission over 150-m and 300-m of MCF. We compare the received EVM of single-antenna systems (that could be seen as a single-input single-output SISO arrangement) with WLAN systems using two antennas (2x2 MIMO) and four antennas (4x4 MIMO). The impact of the quality of the signal in one of the cores of the MCF in the overall MIMO processing is investigated and compared with the results achieved with SISO transmission in each core.

10128-11, Session 6

Bidirectional MIMO and SISO 3GPP LTE-advanced fronthaul architectures based on multicore fiber *(Invited Paper)*

Roberto Llorente Sáez, Maria Morant, Univ. Politècnica de València (Spain)

In the recent years, multi-core fiber (MCF)-based systems have been proposed for optical transmission ranging from the access network to long haul. The use of space division multiplexing (SDM) in MCF targets to overcome the capacity crunch in conventional single-core optical systems.

MCF optical media has been also appointed as a good solution for future 5G wireless cloud radio access network (C-RAN) architectures, capable of feeding different antennas simultaneously from the central office. In this work we critically review the application of MCF systems for optical fronthaul wireless applications with the simultaneous radio-over-fiber (RoF) transmission of 3GPP LTE-Advanced signals in downlink (DL) and uplink (UL) directions. We evaluate experimentally the RoF performance of frequency division duplex (FDD) 3GPP LTE-Advanced signals in different frequency bands from 800 MHz to 3 GHz. Further investigation is performed for FDD LTE band 7 for simultaneous transmission of DL and UL LTE-A signals in opposite directions and different cores in a 4-core MCF. The experimental study evaluates the quality of the received signals in terms of error vector magnitude (EVM) of the data signal and of each channel frame according to the 3GPP wireless standard.

Next-generation C-RAN must provide wireless service to a plurality of antenna units arranged in multiple-input multiple-output (MIMO) configuration. The suitability of the 3GPP wireless standard MIMO processing algorithms applied to MCF optical systems is investigated experimentally. The RoF performance in MCF is evaluated in both SISO and MIMO configurations for comparison. Finally, further research challenges and future studies are discussed.

10128-12, Session 7

Integration of power over fiber on RoF systems in different scenarios *(Invited Paper)*

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In emerging 5G cellular networks able to support massive traffic volumes, traditional macro networks might be densified, and complemented through the addition of small cells. Such a high capacity of the 5G radio environment will boost transport networks to be adapted. The high bandwidth, together with stringent delay and jitter requirements, make dedicated optical connectivity a preferred solution for fronthaul. Those Radio Access Networks (RAN) apart from higher capacity and lower latency should have higher energy efficiency [DOCOMO, 2014]. In order to cover this aspect, power over fiber (PoF) has been pointed out as a key technology for that purpose [Wake et al, 2008] having in mind that control plane will be centralized on future Cloud RAN and that sometimes Remote Radio Heads (RRHs) should be deployed in places lacking external power supply in order to fulfill the desired coverage. PoF is designed avoiding the damage of Fiber Fuse [R. Kashyap, 2013] [Y. Mizuno, 2014]. Different scenarios are considered, in [Miyanabe et al, 2015] the communications between the OLT and the ONU module of the RRHs is provided by a 50/125 silica multimode fiber (MMF) meanwhile in [Vázquez et al, 2016] its counterpart 62.5/125 MMF is considered. Recent PoF proposals include graded index plastic optical fiber [Dayron et al, 2016] being a technology that can support Radio over Fiber (RoF) at high rates [Montero et al, 2011]. There is also a 5G automotive vision to enable the next generation of connected and automated driving and new mobility services (V2X) [5G-automotive, 2015] from both the automotive and telecom industry. Vehicles generally enjoy better connectivity compared to consumer user devices, since more and higher gain antennas can be implemented thanks to lesser space constraints but lighter on-board technologies can provide less fuel consumption on those nomadic nodes.

In this paper, different scenarios on potential demanding environments of power over fiber on RoF systems such as automotive, in-house and remote mobile fronthaul will be discussed.

Some tests on power over fiber systems based on different single mode and MMF will be provided.

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10128-13, Session 7

High-voltage optical power delivery using a light-wave-modulation method

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Optical power-delivery systems are intensively applied for the distribution of electrical power over optical fibers for remote wireless radio heads, remote cameras, sensor devices, short-reach power delivery with data stream, etc. Optical fibers have advantages such as high electrical-isolation characteristics and lightweight transmission lines when compared with metallic electric cable. In a conventional optical power-delivery system, a near-infrared light such as 980-, 1060-, or 1550-nm is widely used because of the low transmission loss available at that waveband over optical fiber, and a continuous wave (CW) light is applied for delivering the DC electrical power to the receiver side. Because the electrical voltage at the receiver side is naturally low, around 1.0 V, which is based on the use of a long-wavelength carrier, a DC-DC up-converter is needed to operate the electrical system. Consequently, we recently proposed a light-wave-modulation method for increasing the received electrical voltage. In the experiment, a 980-nm GaAs-based high-power laser was directly modulated to form a modulated light wave with a square or sinusoidal wave around ~100 MHz at the transmitter side; then a Si photodetector was used to obtain the electrical power with the optical to electrical conversion. We also used a small inductor to generate an induced electromotive force based on Faraday's law from time variation of the modulated light wave. We successfully obtained a high voltage over 18 V at the receiver side using this simple technique. We consider that higher voltages can be obtained by optimizing the modulation frequency and inductance.

10128-14, Session 7

Distribution of multiband THz wireless signals over fibre *(Invited Paper)*

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Higher capacity wireless access networks are required to serve growing demands for increasing mobile traffic and multimedia services. Recently, terahertz wireless communication has been receiving great interest from researchers and industry. New spectral windows at frequencies between 0.1 and 1 THz offer opportunities for ultra-high-data-rate wireless transmission. These bands are wide enough and, above 300 GHz, are not yet allocated. Currently, IEEE 802.15.3 task group 3d is developing standards for 100 Gb/s transmission over ranges from a few centimetres to 200 m in the 252 – 325 GHz band, addressing applications from intra-device communication to wireless backhaul. Wavelength division multiplexing for wireless-over-fibre is foreseen as important to support a huge increase in base stations connected to a central station. This would allow future demands for mm-wave wireless coverage, ease of maintenance, and cost-effectiveness to be met. In this paper, we demonstrate experimentally a new architecture for photonic generation and distribution of multiband signals for sub-THz wireless communications, giving rates up to 100 Gb/s (20 Gb/s in each band) using the full spectrum between 220 and 280 GHz for downlink wireless transmission, and 10 Gb/s for uplink using on-off keying. The sub-THz signals are intended for short-range, indoor links to mobile units. The use of multiple bands increases the total transmitted data rate while reducing the bandwidth requirements on opto-electronic devices. The receiver link budget and wireless distance for acceptable bit error ratio are explored, and the linewidth tolerance is studied numerically to provide a guide to performance with different modulation formats.

10128-15, Session 7

Radio over fiber-based communication systems for high-speed train using 90GHz band

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Due to its larger capacity and lower energy consumption, High-speed train (HST) system is playing very important role in mass transportation. Various Communication systems for HST have been deployed mainly for train control and safety purpose. Growing demand of broadband wireless communication for passengers on the train requires new data transmission technique suitable for high speed and dense user environment. In this paper, distributed antenna systems (DASs) with combination of W-band millimeter communication and radio over fiber (RoF) technology is presented.

The communication system can basically avoid transmission rate decrease due to handover employing RoF based signal distribution architecture. Since ITU-R assigned wide band frequency bands (92.0-94.0, 94.1-100.0, 102-109.5GHz) for mobile system and relatively low propagation loss of the frequency bands, a high data transmission rate more than 1Gb/s per train and cost effective system can be realized. The technical challenges in providing DAS-based communication systems for HSTs include system architecture, RF system design and propagation issue of W-band frequency in a railway environment. Propagation studies in the specific railway environment such as tunnel, cutting and viaduct are investigated. Wide-band single carrier, OFDM and sub-channel single carrier is considered a candidate of the system. Designed and evaluated characteristics of GaAs compound MMICs, system level consideration of RF/IF/RoF link and EVM measurement of wide band modulation signals are discussed and outlined.

10128-16, Session 7

High-throughput and low-latency 60GHz small-cell network architectures over radio-over-fiber technologies *(Invited Paper)*

Nikos Pleros, George Kalfas, Chara Mitsolidou, Christos Vagionas, Dimitris M. Tsiokos, Amalia Miliou, Aristotle Univ. of Thessaloniki (Greece)

Future broadband access networks in the 5G framework will need to be bilateral, exploiting both optical and wireless technologies. This paper deals with new approaches and synergies on radio-over-fiber (RoF) technologies and how those can be leveraged to seamlessly converge wireless technology for agility and mobility with passive optical networks (PON)-based backhauling. The proposed convergence paradigm is based upon a holistic network architecture mixing mm-wave wireless access with photonic integration, dynamic capacity allocation and network coding schemes to enable high bandwidth and low-latency fixed and 60GHz wireless personal area communications for gigabit rate per user, proposing and deploying on top a Medium-Transparent MAC (MT-MAC) protocol as a low-latency bandwidth allocation mechanism. We have evaluated alternative network topologies between the central office (CO) and the access point module (APM) for data rates up to 2.5 Gb/s and SC frequencies up to 60 GHz. Optical network coding is demonstrated for SCM-based signalling to enhance bandwidth utilization and facilitate optical-wireless convergence in 5G applications, reporting medium-transparent network coding directly at the physical layer between end-users communicating over a RoF infrastructure. Towards equipping the physical layer with the appropriate agility to support MT-MAC protocols, a monolithic InP-based Remote Antenna Unit optoelectronic PIC interface is shown that ensures control over the optical resource allocation assisting at the same time broadband wireless service. Finally, the MT-MAC protocol is analysed and simulation and analytical theoretical results are presented that are found to be in good agreement confirming latency values lower than 1msec for small- to mid-load conditions.

10128-17, Session PWed

A geometric model to estimate civil works cost in urban areas

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The NGA networks such as FTTC, FTTB, FTTdp and FTTH have as prerequisite a high expenditure in civil works needed to deploy the fibre cable network. Any business case to calculate the investment requires a proper estimation of the civil works which can be up to 80% of the total CapEx. In particular, starting from the macro geotype parameters, the Urban optical plant estimation Geometric Models (UGM) presented, estimate the infrastructure in terms of digging, ducts, cable paths and lengths.

There are two models called UGM – B and UGM – C. The first model is used in FTTdp/FTTB/FTTH network architecture, while UGM – C is used in FTTC architecture.

These models don't aim to calculate the exact dig length in a specific area or city in the way that GIS tools do (Geographical Information System, as for example MapInfo), which is used on real cases. This is usually time consuming, needs geographic data (not always available) or ad-hoc surveys of the territory.

10128-18, Session PWed

Secure positioning technique based on the encrypted visible light map

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The performance of the conventional visible light (VL) positioning technique is severely dependent on the position of the adjacent VL transmitter or the VL receiver in the three dimensional (3-D) VL channel. For overcoming the performance degradation problems of the conventional VL positioning system, which are due to the co-channel interference by adjacent light and the irregularity of the VL reception position in the VL channel, the secure positioning technique based on the encrypted VL map is considered in this paper. In order to surmount thoroughly the performance degradation problems of the conventional technique, the secure VL positioning methodology based on the two dimensional (2-D) encrypted VL map is proposed in this work, the stream encryption key for the good VL positioning and the optimal 2-D positioning cell in the 3-D channel is investigated through the real positioning experiment. The proposed positioning methodology is implemented as the specific embedded VL positioning prototypes, and verified by performance analysis. Through of the preliminary work by the construction of the 2-D encrypted VL map, we can know that the reception position error problem due to the irregularity of the VL reception position in the 3-D VL channel was absolutely surmounted. We can know from the results of the performance analysis that the increase over 21.7% value of the 2-D positioning cell by the encryption algorithm of the proposed technique causes the mitigation effect of the co-channel interference problem.

10128-19, Session PWed

A comparative study of optical concentrators for visible light communications

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Given the imminent radio frequency spectrum crunch, Visible Light Communication (VLC) is being proposed as an alternative wireless technology allowing for scalable connectivity to potentially millions of mobile and Internet-of-Things (IoT) devices. A VLC system uses a photo-detector (PD) receiver that converts the optically modulated light from a light source into a modulated electrical signal. The corresponding receiver electrical bandwidth is typically inversely proportional to the PD active area. Therefore to construct a high-speed VLC link, the PD active area is often substantially reduced and an optical concentrator is used to enhance the receiver collection area. However, to achieve high concentrating factor, the link field-of-view (FOV) needs to be narrow due to the etendue conservation in linear passive optical systems. This paper studies a Fluorescent Concentrator (FC) that breaks this etendue conservation. The FC is not only based on reflective and refractive principles but also makes use of fluorescence process. A comparison between the FC and conventional optical concentrators such as plano-convex lens and Compound Parabolic Concentrator (CPC) is also investigated. The trade-off between received signal strength and incoming link angle is demonstrated over ±60° degrees coverage. Result shows that performance degradation as the link angle increases using FC-based receivers is significantly lower than for CPC or lens concentrator.

10128-20, Session PWed

High-power InGaAs/InP MUTC photodetectors for RF photonic links and ROF

Kenneth A. Hay, Steven Estrella, Jenna Campbell, Daniel S. Renner, Milan L. Mashanovitch, Leif A. Johansson, Freedom Photonics, LLC (United States)

Freedom Photonics is producer of high-power photodetectors (HPPD) for the 1480 to 1620nm wavelength range. Applications for these HPPDs range from high-power remote antennas, low-duty-cycle RF pulse generation, linear photonic links to high dynamic range optical systems and radio-over-fiber (ROF). Last year, published results showing 20dBm RF power was achieved at 20GHz and 100mA photo current. These Modified Uni-Traveling Carrier (MUTC) photodetectors are now being offered commercially. In 2016 FP has developed a HPPD for similar applications extending into the V-band. The MUTC structure used for these photodetectors is designed to achieve over 100GHz bandwidths. This work details the saturation and bandwidth performance for various size photodiodes, between 6um and 16um in diameter. Measurement data will be presented, which was collected at both wafer level and for fully packaged detectors. For detector devices with bandwidth performance over 50GHz, the generated RF power achieved is over 15dBm. This performance is exceptional considering the photodiode is fully integrated into a hermetic package designed for 65GHz. Improvements in the coplanar waveguide (CPW) transmission line and flip-chip bonding design were integral in achieving the higher saturation at the higher bandwidth performance. Further development toward achieving a >100GHz packaged photodetector module is described relative to the performance obtained at wafer level for the various size photodiode devices.

Conference 10129: Optical Metro Networks and Short-Haul Systems IX

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10129-1, Session 1

Advanced digital signal processing for short haul optical fiber transmission beyond 100G *(Invited Paper)*

Nobuhiko Kikuchi, Hitachi, Ltd. (Japan)

Significant increase of intra and inter data center traffic has been expected by the rapid spread of various network applications like SNS, IoT, mobile and cloud computing, and the needs for ultra-high speed and cost-effective short- to mid-reach optical fiber links beyond 100-Gbit/s is becoming larger and larger. Such high-speed links typically use multilevel modulation to lower signaling speed, which in turn face serious challenges in limited loss budget and waveform distortion tolerance. One of the promising techniques to overcome them is the use of advanced digital signal processing (DSP) and we review various DSP applications for short-to-mid reach applications mainly of our recent research on FPGA prototyping of direct-detection based 16-level 100G/ch transmission, DSP-asissted PAM4 signaling like SSB modulation and DML-distortion suppression and so on.

10129-2, Session 3

Recent advances of optical amplification technology *(Invited Paper)*

Jutaro Miura, Oplink Japan Ltd. (Japan)

The proliferation of a Colorless and Directionless and Contentionless (CD&C) architecture in metro networks is rising up ever-greater demands on optical amplifiers to be smaller and higher integration. we overview recent advances in optical amplifier technologies, multiple EDFA arrays for compensating loss of a multicast switch and switchable gain EDFAs supporting a wide range of fiber-span loss distributions in the network and focus on the embedded passive component and pump laser in the amplifiers. We will also focus on the pluggable small form factor EDFA amplifies optical signals to enable long Hybrid Fiber Coaxial (HFC) links and/or high optical splitting for RF-over-Glass architectures.and amplifier for CFP-DCO/CFP2-ACO transceiver. Finally, we will discuss the feasibility of L-band amplifier and distribution Raman amplifier in a short-haul systems to realize a requisite optical signal to noise ratio (OSNR) to support high bit rate transmission beyond 100G and high capacity transmission.

10129-3, Session 4

Optical mm-wave beam steering for 5G: integrated circuits and fiber systems *(Invited Paper)*

Zizheng Cao, Technische Univ. Eindhoven (Netherlands); Xin Yin, Univ. Gent (Belgium); Antonius M. J. Koonen, Technische Univ. Eindhoven (Netherlands)

Recently, the desired very high throughput of 5G wireless networks drives millimeter-wave (mm-wave) communication into practical applications. Phased array technique is required to increase the effective antenna aperture at mm-wave frequency. Integrated solutions of beam-forming/-steering are extremely attractive for practical implementations. In this talk, we review our recent progress and latest research on optical mm-wave beam steering. The remotely tunable integrated mm-wave beamformer based on optical true time delay is explored. The on-chip TTD network is realized by the architecture of arrayed waveguide grating feedback loop. The high-speed photo-diodes (>40GHz) are also integrated to reduce the package-induced power loss and cost. To allow its application in practical scenarios, the electronic integrated circuits including multiple-channel automatic power controlled trans-impedance amplifiers are designed to accommodate the electrical signal after photodiodes. Based on the integrated circuits, we have successfully demonstrated a 38-GHz beam-steered fiber-wireless system for 5G indoor coverage.

10129-4, Session 4

InP PIC technologies for high-performance Mach-Zehnder modulator *(Invited Paper)*

Yuta Ueda, Yoshihiro Ogiso, Nobuhiro Kikuchi, Nippon Telegraph and Telephone Corp. (Japan)

We have developed compact InP-based Mach-Zehnder modulators (MZMs) for small-form-factor pluggable coherent transceivers. In the presentation, we introduce InP-based photonic integration circuit (PIC) technologies for high-performance MZMs. As a first topic of the presentation, we show a design concept of a multi-quantum well (MQW) with a large refractive-index change and a low excess loss for a low-driving-voltage and low-loss MZM. We fabricated a DP-IQ modulator in the form of a monolithically integrated quad MZM based on the designed MQW, and it operated at a half-wavelength voltage of 1.9 V with less than 1-dB excess loss as designed. A 32G-baud DP-QPSK operation with a 0.2-dB penalty compared to a lithium niobate modulator was achieved. We also show another newly developed high-speed IQ-modulator for beyond 100G systems. We reduced an RF signal loss of an MZM by adopting low resistance overclad material and optimizing the RF circuit structure. A fabricated high-speed IQ modulator operated at higher than 64G baud with QPSK/16QM modulations. Furthermore, we present an InP-MZM integrated with a new type of spot-size converter (SSC) fabricated by three-dimensional semiconductor process. The SSC integrated MZM exhibited an improved insertion loss by ~3dB compared to our conventional InP-MZM for an optical system with a 4.5-um mode filed diameter. The low loss characteristics are beneficial to reduction of an MZM-module cost due to an improved loss budget in optical assembling.

10129-5, Session 5

S-BVT for next-generation optical metro networks: benefits, design, and key enabling technologies *(Invited Paper)*

Michela Svaluto Moreolo, Josep M. Fabrega, Laia Nadal, Ctr. Tecnològic de Telecomunicacions de Catalunya (Spain)

Driven by novel and bandwidth-hungry services, and the need for heterogeneous and data-intensive traffic aggregation/delivery, a migration towards a more dynamic, efficient and agile paradigm is envisioned for optical metro networks.

To address the challenges and requirements of this scenario, the sliceable bandwidth/bitrate variable transceiver (S-BVT) appears as an attractive solution, when suitably tailored for this network segment.

This work contributes to elaborate on three main questions about the use of S-BVT in next-generation optical metro networks: i) why the S-BVT represents a key enabler; ii) how it should be designed to take benefits of its capabilities and advanced features; and iii) which are the most relevant requirements to be satisfied, the limitations to be addressed/overcome and the promising technologies to be adopted.

Particularly, cost-optimized modular architecture designs enable multi-adaptive software-defined optical transmission. The adoption of multicarrier modulation and flexi-grid technologies for on-demand spectral manipulation

with fine granularity is envisioned to be combined with cost-effective optoelectronic front-ends.

Furthermore, multiple dimensions exploiting orthogonal band multiplexing and/or polarization multiplexing can be adopted, with a limited number of building blocks, enhancing the S-BVT capacity and spectral efficiency to support traffic from/to multiple tenants in highly flexible/scalable software-defined optical metro networks.

The proposed S-BVT with advanced monitoring capabilities enables efficient SDN programming and resources saving, coping with the cost/energy requirements of optical metro networks.

This together with the adoption of suitable photonic technologies, limiting the complexity and cost of the implementation, will draw the way towards cost-efficient, dynamic and software-defined optical metro networks.

10129-6, Session 5

Logical optical line terminal technologies towards flexible and highly reliable metro- and access-integrated networks *(Invited Paper)*

Satoru Okamoto, Takehiro Sato, Naoaki Yamanaka, Keio Univ. (Japan)

In this paper, flexible and highly reliable metro and access integrated networks with network virtualization and software defined networking technologies will be presented.

Logical optical line terminal (L-OLT) technologies and active optical distribution networks (ODNs) are the key to introduce flexibility and high reliability into the metro and access integrated networks. In the Elastic Lambda Aggregation Network (E?AN) project which was started in 2012, a concept of the programmable optical line terminal (P-OLT) has been proposed. A roll of the P-OLT is providing multiple network services that have different protocols and quality of service requirements by single OLT box. Accommodated services will be Internet access, mobile front-haul/back-haul, data-center access, and private line. L-OLTs are configured within the P-OLT box to support the functions required for each network service. Multiple P-OLTs and programmable optical network units (P-ONUs) are connected by the active ODN. Optical access paths which have flexible capacity are set on the ODN to provide network services from L-OLT to logical ONUs (L-ONUs). The L-OLT to L-ONU path on the active ODN provides a logical connection. Therefore, introducing virtualization technologies become possible. One example is moving an L-OLT from one P-OLT to another P-OLT like a virtual machine. This movement is called L-OLT migration. The L-OLT migration provides flexible and reliable network functions such as energy saving by aggregating L-OLTs to a limited number of P-OLTs, and network wide optical access path restoration. Other L-OLT virtualization technologies and experimental results will be also discussed in the paper.

10129-7, Session 5

Routing in EON networks under mixed static and dynamic traffic

Karcius Day Rosario Assis, Alex Santos, Federal Univ. do Recôncavo of Bahia (Brazil); Igor M. Queiroz, Univ. Federal da Bahia (Brazil)

This paper proposes heuristics, which can maximize the number of remaining available routes and minimize the number of transceivers in Elastic Optical Networks (EON). The aim of the proposal is to preserve the open capacity for the accommodation of future unknown dynamic demands. Case studies are carried out in order to analyze the performance of the heuristic in several networks. The results suggest that it is feasible to preserve enough open capacity to avoid blocking of future requests in EON with scarce resources.

Firstly we used a static RSA and after that a dynamic RSA. Therefore, the nework is like a loose topology, i.e. a multi-client physical topology that must accommodate both static and dynamic traffic demands.

The key proposal are heuristics for static traffic demand, which are oriented towards optimizing the residual network capacity for the accommodation of future unknown dynamic demands, while guaranteeing the establishment of a predefined traffic demand. The heuristic for the static trtaffic consider that the virtual topology is given.The computational experiments clearly show that our approaches with heuristics give good solutions to maximizing the number of remaining routes for the dynamic traffic, making efficient use of resources.

10129-8, Session 5

Network expansion strategy for elastic optical networks that considers channel capacity upgrades

Takuma Yasuda, Yojiro Mori, Hiroshi Hasegawa, Ken-ichi Sato, Nagoya Univ. (Japan)

Networks must expand with the continual traffic growth. Network capacity enhancement promotes the introduction of new higher bitrate transmission systems such as 400G/1Tbps channels in addition to present 10/40/100 Gbps channels. The former occupies broader frequency bandwidths than the latter and the efficient introduction of different bandwidth channels requires fine granularity frequency bandwidth allocation with a flexible grid. The accommodation of non-uniform bandwidth channels suffers from the fragmented slot allocation in the frequency domain. Several studies on mitigating this fragmentation have been presented, however, they focused on the greenfield design case and failed to address the more realistic situation of periodic network expansion where channel capacity increases as the technology advances and newly arriving connection requests must be processed. In order to minimize the frequency slot fragmentation under dynamic network expansion, we propose to introduce aligned frequency assignment to each bandwidth channel, i.e., the semi-flexible grid. In semi-flexible grid networks, for each set of channels having the same frequency bandwidth, a regular grid is defined so that its spacing becomes same as the required bandwidth. These channels are aligned to their corresponding grids. A network expansion algorithm is developed that maximizes the efficiency of semi-flexible grid assignment. It enables smooth channel bandwidth upgrades. Numerical experiments prove that the number of fibers necessary and the degree of fragmentation in the frequency domain are reduced by 15% and 80%, respectively, compared to conventional flexible grid networks accommodating the same traffic.

10129-9, Session 5

100-Gb/s OFDM/OQAM over 100-km transmission based on guard-band-shared direct-detection scheme *(Invited Paper)*

Qi Yang, Wuhan Research Institute of Posts and Telecommunications (China); Chao Li, Univ. of Electronic Science and Technology of China (China); Xiang Li, Wuhan National Lab. for Optoelectronics (China)

In this paper, we propose guard-band-shared direct-detection (GBSDD) scheme to simultaneously receive multi-band 100-Gb/s direct-detection optical signal with only one conventional 40-GHz photodiode. The modulation format of orthogonal frequency-division multiplexing based on offset quadrature amplitude modulation (OFDM/OQAM) is selected to provide signal spectrum with high side-lobe suppression ratio, which can effectively reduce the electrical sub-band frequency interference. In GBSDD scheme, only one guard band is required to accommodate the overlapped signal-to-signal beat interference (SSBI) induced by all the multi-band optical signals. Three different GBSDD schemes are experimentally demonstrated with total data rate of 100-Gb/s and OFDM/OQAM modulation format. The first one uses 6 sub-bands with transmission distance of 320 km and hybrid 32-QAM and 16-QAM formats. 6 lasers are used as the pilot carriers to beat the signal. The seconds utilizes only 2 sub-bands with 64-QAM format in 80-km fiber transmission, which are assigned onto two orthogonal polarizations. Only one optical pilot carrier is inserted to beat with the 2 sub-bands on the two polarizations. The 2 sub-bands are located on the one side of the optical carrier. Comparing with the first scheme, the bandwidth usage of the PD is enhanced from 1/2 to 2/3. In the third scheme, the 100-Gb/s optical signal includes 4 sub-bands with 32-QAM format after 880-km fiber transmission. The 4 sub-bands locate at the two sides of the optical pilot subcarrier. Under this condition, the bandwidth usage of the PD is further improved from 2/3 to 4/5.

10129-10, Session 6

Silicon photonics devices for metro applications *(Invited Paper)*

Hiroshi Fukuda, Nippon Telegraph and Telephone Corp. (Japan); Kiyofumi Kikuchi, Makoto Jizodo, Yuriko Kawamura, Kotaro Takeda, Kentaro Honda, NTT Device Technology Labs. (Japan)

Digital coherent technology is considered an attractive way of realizing both high-speed metro links and long distance transmissions. In metro areas, there is a strong demand for a smaller faster transceiver module. This demand is mainly driven by the rapidly increasing data center interconnection traffic, where transmission capacity per faceplate is a key feature. Therefore, optical integration technology is desired.

Since compensation in digital coherent technology is performed in the electrical or digital domain, users can deal with those optics performances that are not compensated for digitally. This means it is possible to employ a new material that cannot provide perfect characteristics but that is suitable for miniaturization and integration.

Silicon photonics (SiPh) is considered an attractive technology that would enable the significant miniaturization of optical circuits and be capable of optical integration with high manufacturability. While SiPh-based devices have begun to be deployed for very short or short reach links based on direct detection technology, their digital coherent applications have recently been investigated in view of their integration capability.

This paper describes recent progress on SiPh-based integrated optical devices for high-speed digital coherent transceivers targeting metro links. An optical modulator and receiver with related circuits have been integrated into a single SiPh chip. TEC-free operation under non-hermitic conditions and the direct attachment of optical fibers have both been realized. Very thin and small packaging with sufficient performance has been demonstrated by using the SiPh chip co-packaged with high-speed analog ICs.

10129-11, Session 7

Field demonstration of real-time 100G-PON *(Invited Paper)*

Lilin Yi, Honglin Ji, Weisheng Hu, Shanghai Jiao Tong Univ. (China)

As the demand for broadband applications continues rising, low cost and high capacity PON system has attracted more attention to keep up with the increasing demand in the future access network. Recently, the IEEE 802.3 Ethernet Working Group has already sponsored the discussion of next generation Ethernet passive optical network (NG-EPON) to provide 25-Gb/s per wavelength. In order to upgrade current 10-Gb/s PON to realize the capacity of 100 Gb/s PON with 25 Gb/s per wavelength, a variety of experimental demonstrations have shown the feasibility of 25-Gb/s per wavelength using the modulation schemes of four-level pulse amplitude modulation (PAM-4), electrical duobinary (EDB), optical duobinary (ODB) or non-return-to-zero on-off-keying (NRZ-OOK) for high speed transmission. In order to achieve higher performance, these transmission schemes are always combined with the advanced digital signal processing (DSP) which increases the technical complexity and the cost as well. Most of the previous demonstration are based on the off-line processing, therefore requires more time for the practical deployment.

In this paper, we demonstrate the first field trial a real-time 100Gb/s TWDM-PON system with 4?25-Gb/s downstream and 4?10-Gb/s upstream transmission using 10G-class directly-modulated lasers (DMLs) and APD/PIN receivers. A single delay-interferometer (DI) is used to achieve frequency equalization as well as chirp management to increase the high frequency components of the system response and combat the chromatic dispersion (CD) during the fiber transmission. Note that there is no DSP applied for the whole system. Electrical clock/data recovery (CDR) chips are integrated on the main board for data generation, recovery and real-time bit error rate (BER) measurement. We obtained a power budget of 33 dB with 0-40km of standard single mode fiber based on NRZ-OOK modulation format for the downstream. The system stability is also verified using deployed 40-km fiber infrastructure over 67-hour real-time measurement.

10129-12, Session 7

Nonlinear compensation for high-order modulation signal in a IM/DD DFT-S-OFDM system with directly modulated laser

Kaihui Wang, Chaoyi Qin, Jiangnan Xiao, Nan Chi, Jianjun Yu, Fudan Univ. (China)

The nonlinear compensation algorithm based on Volterra series has been proved effective in low order modulation OFDM system, such as QPSK/16QAM. In this paper, we demonstrate a 64QAM/ 128QAM DFT-S-OFDM signal generation with DML with some advanced algorithms such as DD-LMS, ISFA, DFT-S and nonlinear compensation to improve the signal performance. For the first time we demonstrate that the nonlinear compensation algorithm based on Volterra series can improve the performance of the high-order modulation DFT-S-OFDM signal such as 64QAM and 128QAM. In this experiment we have realized 19.1/11.2Gb/s 64/128QAM signal transmission over 15km fiber at 1307nm. For 64QAM case, the receiver sensitivity can be improved about 1dB when all the algorithms mentioned in this paper are adopted. And the BER can be improved from 4.7x10-3 to 2.8x10-3 at 7.0dBm for 128QAM signal, which reaches the HD-FEC threshold of 3.8x10-3.

10129-13, Session 8

Analysis of nonlinearity mitigation using spectral inversion in superchannel transmission *(Invited Paper)*

Inwoong Kim, Olga Vassilieva, Paparao Palacharla, Tadashi Ikeuchi, Fujitsu Labs. of America, Inc. (United States)

Nonlinearity mitigation (NLM) is required to extend optical reach of spectrally efficient superchannel transmission with higher order modulation formats. NLM by spectral inversion (SI) has been believed to be impractical because of required link symmetry with respect to SI. We show that SI still can mitigate significant nonlinearity in non-symmetric link configurations. We also developed an analytical model to estimate NLM by SI in arbitrary link configurations and SI placement. Especially, the impact of link symmetry on inter-subcarrier and intra-subcarrier NLM by SI in superchannel transmission is evaluated by simulation and explained by the analytical model.

10129-14, Session 8

Simultaneous 10 Gbps data and polarization-based pulse-per-second clock transmission using a single VCSEL for high-speed optical fibre access networks

George Isoe, Shukree Wassin, Nelson Mandela Metropolitan Univ. (South Africa); Romeo Gamatham, SKA South Africa (South Africa); Andrew W. R. Leitch, Tim B. Gibbon, Nelson Mandela Metropolitan Univ. (South Africa)

Access networks based on vertical cavity surface emitting laser (VCSEL) transmitters offer alternative solution in delivering different high bandwidth, cost effective services to the customer premises. Clock and reference frequency distribution is critical for applications such as Coordinated Universal Time (UTC), GPS, banking and big data science projects. Simultaneous distribution of both data and timing signals over shared infrastructure is thus desirable. In this paper, we propose and experimentally demonstrate a novel, cost-effective technique for multi-signal modulation on a single VCSEL transmitter. Two signal types, an intensity modulated10 Gbps data signal and a polarization-based pulse per second (PPS) clock signal are directly modulated onto a single VCSEL carrier at 1550 nm. Spectral efficiency is maximized by exploiting inherent orthogonal polarization switching of the VCSEL with changing bias in transmission of the PPS signal. A 10 Gbps VCSEL transmission with PPS over 25.5 km of G. 655 SMF-SRS fibre introduced a transmission penalty of 1.01 dB. The contribution of PPS to this penalty was found to be 0.15 dB.

10129-15, Session 8

Highly accurate pulse-per-second timing distribution over optical fibre network using VCSEL side-mode injection

Shukree Wassin, George M. Isoe, Nelson Mandela Metropolitan Univ. (South Africa); Romeo R. G. Gamatham, SKA South Africa (South Africa); Andrew W. R. Leitch, Tim B. Gibbon, Nelson Mandela Metropolitan Univ. (South Africa)

Abstract – Precise and accurate timing signals distributed between a centralized location and several end-users is widely used in both metro-access and speciality networks for Coordinated Universal Time (UTC), GPS satellite systems, banking, very long baseline interferometry and science projects such as SKA radio telescope. Such systems utilize time and frequency technology to ensure phase coherence among data signals distributed across an optical fibre network. For accurate timing requirements, precise time intervals should be measured between successive pulses. In this paper we describe a novel, all optical method for quantifying one way propagation times and phase perturbations in the fibre length, using side mode injection of a 1550nm 10G vertical cavity surface emitting laser (VCSEL) at the remote end. A 1.25 x 10-4 s one way time of flight was accurately measured for 25 km G655 fibre. Since the approach is all optical, it avoids measurement inaccuracies introduced by electro-optical conversion phase delays. Furthermore, the implementation uses cost effective VCSEL technology suitable for a flexible range of network architectures that supports a number of end-users conducting measurements at the remote end.

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10130-1, Session 1

Classical key distribution in optical communication *(Invited Paper)*

Guifang Li, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Yaron Bromberg, The Hebrew Univ. of Jerusalem (Israel); Brandon Redding, Sébastien Popoff, Yale Univ. (United States); Ningbo Zhao, Tianjin Univ. (China); Hui Cao, Yale Univ. (United States)

In this talk, we present classical key distribution (CKD) in optical communication.including steganography/bounded-storage CKD and 2) random channel cryptography/bounded-observability CKD.

10130-2, Session 3

Coupled multicore fiber for space-division multiplexed transmission *(Invited Paper)*

Tetsuya Hayashi, Sumitomo Electric Industries, Ltd. (Japan)

We will review our recent studies on the coupling mechanism and differential modal group delay characteristics of the coupled multi-core fiber, and the fabrication results of 125-μm-cladding coupled four-core fibers which realized the record-low spatial mode dispersion (SMD) of 3.14±0.17 ps/√km and the ultra-low attenuation of 0.158 dB/km at 1550 nm, both of which are the lowest ever reported among optical fibers for the space-division multiplexed transmission. The SMD was observed to be proportional to the fiber bend curvature, i.e., inversely proportional to the bend radius, and the SMD of 3.14±0.17 ps/√km was measured at the bending radius of ~31 cm. We expect further SMD suppression by enlarging the bending radius of the fiber. By assuming the 3.14-ps/√km SMD accumulation, the tap count of the multiple-input-multiple-output digital signal processing for the crosstalk compensation is estimated to be only 63 taps for covering 99.99% power of the impulse response after 10,000-km propagation when the 25-GBaud (50-GHz sampling) is assumed. The present results demonstrate the strong and practical applicability of the coupled multi-core fiber to the ultra-long-haul submarine transmission system.

10130-3, Session 3

Recent progress in SDM amplifiers *(Invited Paper)*

Yongmin Jung, Qiongyue Kang, Saurabh Jain, Shaif-Ul U. Alam, David J. Richardson, Univ. of Southampton (United Kingdom)

Space division multiplexing (SDM) utilizing few-mode fibers or multicore fibers supporting multiple spatial channels, is currently under intense investigation as an efficient approach to overcome the current capacity limitations of high-speed long-haul transmission systems based on single mode optical fibers. In order to realize the potential energy and cost savings offered by SDM systems, the individual spatial channels should be simultaneously multiplexed, transmitted, amplified and switched with associated SDM components and subsystems. In this paper, a review of recent progress on the implementation of various SDM amplifiers and its related SDM components will be introduced. Over the last 6 years, various SDM amplifiers have been developed with different SDM fibers, the number of spatial channels and pumping schemes. First, we will summarize/classify the state-of-the-art SDM amplifiers and discuss the structure of the amplifier and their optical properties. Secondly, recently developed fully integrated SDM amplifiers and SDM optical isolators will be discussed in detail. Improved sharing of the optical components and significant device integration were achieved in these devices as required to obtain the anticipated cost reduction benefits of SDM. Finally, the prospect of further scaling with respect to the number of spatial channels that can be amplified will be described.

10130-4, Session 3

Integrated optical fiber amplifiers for space-division multiplexed systems *(Invited Paper)*

Haoshuo Chen, Bell Labs, Nokia Corp. (United States); Cang Jin, Bin Huang, Nicolas K Fontaine, Roland Ryf, René-Jean Essiambre, Bell Labs, Nokia (United States); Younès Messaddeq, Sophie LaRochelle, COPL, Université Laval (Canada)

In recent years, space-division multiplexing (SDM) has experienced fast development in fibers and its associated technologies including passive optical components such as spatial multiplexers as well as active components such as Raman and erbium-doped fiber amplifiers (EDFA). Optical amplifiers are a key building block of optical networks and are inevitable for long-distance transmission to compensate for fiber losses.

Cladding pumping uses a different set of modes for the pump light and the signal light, which can use mode-multiplexing to combine the pump and signal light rather than wavelength multiplexer applied for core pumping. Cladding-pumped EDFA can get rid of wavelength multiplexer, allows the use of one cost-efficient high-power multi-mode laser-diode as pump source, and enables simple mode-multiplexed coupling schemes such as edge-coupling and side-coupling.

This abstract will discuss the advantages and challenges of cladding-pumped EDFAs. Recently demonstrated integrated multicore cladding-pumped EDFAs will be presented, which deliver high output power and low noise figure over the C-band.

10130-5, Session 4

Novel paradigm for integrated photonics circuits: transient interconnection network

Eugenio Fazio, Alessandro Belardini, Lorenzo Bastiani, Massimo Alonzo, Sapienza Univ. di Roma (Italy); Mathieu Chauvet, Univ. de Franche-Comté (France); Nikolay I. Zheludev, Univ. of Southampton (United Kingdom) and Nanyang Technological Univ. (Singapore); Cesare Soci, Nanyang Technological Univ. (Singapore)

Spatial solitons were investigated from the theoretical point of view but up to know no devices based on them was really proposed. Considering electro-optic solitons, the application of external electric bias turned to be fundamental to induce the correct nonlinearity to induce selfocusing and then self confinement. However, no engineering of the external biases was never proposed (to our knowledge) in order to design complex systems.

We start our work on the idea to have 2 different laser systems, one to write the circuit and one that carry the information.

Moreover we have design and engineered specific electric biases to make the self-confined waveguides:

to be deflected at different angles or to travel straight;

to interact one-each in X and Y junction configurations;

such junctions can be linear and nonlinear, in the sense that the coupling efficiency for the signal beam between soliton channels can be externally addressed for example by the intensity of a specific channel;

transient interconnections can be realized, with living times that depend on the specific needs, in order to open permanent communication channels or very fast and transient ones (like for example in brain synapsis, that can be volatile or long living according to the needs).....and so on.

The performed work is both theoretical (by means of numerical simulations of linear and nonlinear beam propagation in electro-optic insulating crystals or fast semiconductors). Experimental evidence of some proposed devices will be presented (for example an active electro-optical deflector on an fully addressable X junction). Some of these devices are at the moment under patenting.

10130-6, Session 5

Multicore fiber transmission over transoceanic distances *(Invited Paper)*

Alexey Turukhin, TE Connectivity Subsea Communications (United States)

We show how spatial division multiplexing (SDM) can be used to increase both power efficiency and capacity of transoceanic transmission. Power efficiency is particularly important for transoceanic systems in which the electrical pump power required for optical amplification must be distributed over thousands of kilometers. We describe a number of power efficient modulation formats and optical system design techniques that can be used with SDM to simultaneously achieve high capacity and power efficiency. Experimental demonstrations in 12-core fiber showing the feasibility of 105.1 Tb/s transmission over 14,350 km with C-Band amplification as well as 0.52Pb/s transmission over 8,830km using 9THz of optical bandwidth enabled by C+L band EDFAs are discussed.

10130-7, Session 5

Mode-converter and multiplexer based on SOI technology for few-mode fiber at 1550 nm

David Garcia Rodriguez, Juan Luis Corral Gonzalez, Amadeu Griol Barres, Roberto Llorente Sáez, Valencia Nanophotonics Technology Ctr., Univ. Politécnica de Valencia (Spain)

The Asymmetric Directional Coupler (ADC) based on SOI (Silicon-on-Insulator) technology converts and couple the fundamental mode to the first higher order mode. The ADC is designed to achieve phase matching condition, which is accomplished when both propagation constants are equal in each waveguide arm. Devices are fabricated in a SOI wafer with a 220 nm thick silicon layer. The refractive indexes of Si and SiO2 are nSi=3.47 and nSiO2=1.46 respectively. The access waveguides (W1=0.45 ?m) have been designed to propagate just the fundamental mode, TE0. The optimum width for the waveguide 2 was chosen to achieve the phase-matching condition for the TE1 mode, which corresponds to W2=0.962 ?m.

The coupling to the input and output waveguide is achieved through the grating coupler. The input grating coupler will need to couple the LP01 mode from the SSMF (Single-Standard Mode Fiber) to the TE0 mode in the SOI waveguide; thus a typical design for a SOI coupler can be used. However, the output coupler must simultaneously couple the TE0 and TE1 modes in the SOI wide waveguide to the LP01 and LP11 modes in the FMF (Few-mode Fiber). Input gratings are designed to have an area of 12x12 ?m2 and a period of ?=610 nm in order to maximize the optical power coupled between the fiber and the waveguide for an incident angle of 10 degrees. Output gratings are designed with the same period but distinct area (12.5x12.5 ?m2) to correctly couple the LP01 and LP11 modes in the FMF.

10130-8, Session 5

All-fiber mode selective couplers for mode-division-multiplexed optical transmission *(Invited Paper)*

Sun Hyok Chang, Kwangjoon Kim, Joon Ki Lee, Electronics and Telecommunications Research Institute (Korea, Republic of)

All-fiber mode selective coupler (MSC) is comprised of a few mode fiber (FMF) arm and a single mode fiber (SMF) arm, coupling the LP01 mode of the SMF to a specific higher-order mode (HOM) of the FMF. In order to achieve higher coupling ratio and lower insertion loss, phase-matching condition between the LP01 mode of SMF arm and the HOM of FMF arm should be satisfied. It can be manufactured in the form of a polished-type coupler or fused-type coupler.

We proposed a mode multiplexer that was composed of consecutive MSCs. It multiplexed or demultiplexed LP01, LP11, LP21, and LP02 modes simultaneously by cascading LP11, LP21, and LP02 MSCs. We demonstrated successful transmission of three modes with 120 Gb/s DP-QPSK signals over 15 km of the FMF by using the all-fiber mode multiplexer.

In order to enhance the signal transmission performance, a mode multiplexer to utilize two-fold degenerate LP11 modes was proposed. It was composed of two consecutive LP11 MSCs that allowed for the multiplexing of LP01 mode and two orthogonal LP11 modes. We demonstrated WDM transmission of 32 wavelength channels with 100 GHz spacing, each carrying 3 modes of 120 Gb/s DP-QPSK signal, over 560 km of FMF.

In this paper, the manufacturing method and the recent advancement of the all-fiber mode multiplexer based on the MSCs are reviewed. Long-distance mode division multiplexing (MDM) optical signal transmissions with the all-fiber mode multiplexer are experimentally demonstrated.

10130-9, Session 5

Mode-division-multiplexing passive optical network with low-modal crosstalk *(Invited Paper)*

Juhao Li, Peking Univ. (China)

In this paper we present the concepts of multidimensional PONs based on MDM including MDM-PON, MDM-TDM-PON, MDM-WDM-TDM-PON and review recent results in this area. Direct detection is used in all the proposed PON systems based on MDM, which avoids the use of coherent detection and MIMO DSP. The all-fiber mode MUX/DeMUX are composed of MSCs, which simultaneously multiplex or demultiplex LP01 and LP11 modes. FMCs are realized by FMF MZI, which are used to realize bidirectional transmission.

Owing to low modal crosstalk for FMF transmission, mode MUX/DeMUX and FMCs, we successfully achieve bidirectional MDM-PON transmission, where two independent linearly polarized spatial modes are simultaneously transmitted over 10-km low-modal crosstalk two-mode FMF and demultiplexed without MIMO DSP.

We also report cascaded MDM-TDM-PON demonstration. Both downstream and upstream MDM-TDM transmissions are experimentally demonstrated over 10-km two-mode FMF and 10-km SSMF with error-free performance.

Bidirectional MDM-WDM-TDM-PON architecture is also experimentally demonstrated. The bidirectional transmission is achieved by a FMC at the input port of the two-mode FMF for downstream transmission and a SMC in each ONU. The results indicate that this TDM-WDM-MDM-PON architecture is backward compatible with conventional WDM-TDM-PON and can be used to construct larger-scale access network.

10130-10, Session 5

Strategies and resources of mode-division-multiplexed optical fibre transmission based on LP and orbital angular momentum modes *(Invited Paper)*

Ziyang Hu, Univ. of Bristol (United Kingdom); Jie Liu, Sun Yat-sen University (China); Xuyang Wang, Jiangbo Zhu, Siyuan Yu, Univ. of Bristol (United Kingdom)

We present research into the capacity and spectral efficiency of various mode division multiplexed (MDM) transmission schemes in optical fibres, including MIMO schemes based on spatial modes, linearly polarised (LP) modes, and orbital angular momentum (OAM) modes. We estimate the spectral efficiency by calculating the transmission matrix and considering mode coupling under different aperture-bandwidth product. We also consider the signal-processing prefix for LP-MIMO and OAM based technologies to calculate the effective spectral efficiency. Simulation results show LP-MIMO with step-index fibre has higher spectral efficiency than both LP-MIMO with graded-index fibre and OAM, while LP-MIMO with graded-index fibre has the same level of spectral efficiency as OAM. In particular, we compare the computational resources required to support the signal processing algorithms in order to achieve certain amount of capacity or spectral efficiency. We estimate the computational resources by adopting high-performance VLSI architecture and spatial light modulator (SLM) based OAM multiplexing crosstalk equalisation schemes. We reveal the scaling of computational resources with capacity in different MDM schemes. We demonstrate that OAM based schemes have the lowest computational resource requirement and offers a much higher spectral efficiency with limited computational resource. We also show that OAM based schemes could save significant signal processing hardware costs due to its low computational resource requirement. We will also discuss memory size requirements in the LP-MIMO and OAM technologies as results of group delays in multimode fibres.

10130-11, Session 5

Overcoming the capacity crunch: ITU-T G.657.B3 compatible 7-core and 19-core hole-assisted fibers

Anna Ziolowicz, InPhoTech SP z o. o. (Poland) and Warsaw Univ. of Technology (Poland); Lukasz Szostkiewicz, Lukasz Ostrowski, Polskie Centrum Fotoniki i ?wiat?owodów (Poland); Tadeusz Tenderenda, Marek S. Napiera?a, InPhoTech SP z o. o. (Poland); Michal Szymanski, Michal Murawski, Polskie Centrum Fotoniki i ?wiat?owodów (Poland); Marta Filipowicz, InPhoTech SP z o. o. (Poland); Beata Bienkowska, Polskie Centrum Fotoniki i ?wiat?owodów (Poland); Agnieszka Ko?akowska, Anna Pytel, Zbigniew Holdynski, InPhoTech SP z o. o. (Poland); Daniel Kunicki, Polskie Centrum Fotoniki i ?wiat?owodów (Poland); Dawid Budnicki, InPhoTech SP z o. o. (Poland); Krzysztof Poturaj, Univ. of Maria Curie-Sklodowska (Poland); Grzegorz Wójcik, Maria Curie-Sklodowska Univ. (Poland); Mariusz Makara, InPhoTech SP z o. o. (Poland); Pawel Mergo, Univ. of Maria Curie-Sklodowska (Poland); Tomasz Nasilowski, InPhoTech SP z o. o. (Poland)

In order to meet the constantly increasing demand for capacity in optical systems, transferring the concept of spatial multiplexing from laboratory tests to reality is required. We present the designed and manufactured 7-core and 19-core fibres and their characteristics which can be efficiently used in new generation transmission systems. The hole-assisted structure of the presented fibres has been designed to assure negligible core-to-core crosstalk (below -35dB) and to enable the fulfilment of the ITU-T G.652 recommendation for each core. Compatibility is maintained in terms of modal properties (single mode propagation, mode field diameter), dispersion characteristics (zero dispersion wavelength within the range 1300-1324 nm, dispersion slope below 0.095 ps/(nm·km2), and dispersion at 1550 nm below 18.5 ps/(nm·km)), and transmission loss. Each core is also bend-insensitive (less than 0.1dB at 10 turns on a mandrel with 10 mm diameter) such that the requirements of the most demanding recommendation of ITU-T G.567.B3 are fulfilled. Fibers can be used together with other multiplexing methods like DWDM as well as with commercially available dispersion compensating systems. The idea of the fiber will be also broadened to use mode-division multiplexing in the near future. Dedicated fan-in/fan-outs have been created in order to make immediate use in industry possible. The idea of applying a hole-assisted for 19-core fiber with single-mode cores is being presented for the very first time.

10130-12, Session 6

Scalable modulation technology and the tradeoff of reach, spectral efficiency, and complexity *(Invited Paper)*

Gabriella Bosco, Dario Pilori, Pierluigi T. Poggiolini, Andrea Carena, Fernando Guiomar, Politecnico di Torino (Italy)

Bandwidth and capacity demand in metro, regional, and long-haul networks is increasing at several tens of percent per year, driven by video streaming, cloud computing, social media and mobile applications. To sustain this traffic growth, an upgrade of the widely deployed 100-Gb/s long-haul optical systems, based on polarization-multiplexed quadrature phase-shift keying (PM-QPSK) modulation format associated with coherent detection and digital signal processing (DSP), is mandatory. In fact, optical transport techniques enabling a per-channel bit rate beyond 100 Gb/s have recently been the object of intensive R&D activities, aimed at both improving the spectral efficiency and lowering the cost per bit in fiber transmission systems.

In this invited contribution, we review the different available options to scale the per-channel bit-rate to 400 Gb/s and beyond, i.e. symbol-rate increase, use of higher-order quadrature amplitude modulation (QAM) modulation formats and use of super-channels with DSP-enabled spectral shaping and advanced multiplexing technologies. In this analysis, trade-offs of system reach, spectral efficiency and transceiver complexity are addressed.

Besides scalability, next generation optical networks will require a high degree of flexibility in the transponders, which should be able to dynamically adapt the transmission rate and bandwidth occupancy to the light path characteristics. In order to increase the flexibility of these transponders (often referred to as "flexponders"), several advanced modulation techniques have recently been proposed, among which sub-carrier multiplexing, hybrid formats (over time, frequency and polarization), and constellation shaping. We review these techniques, highlighting their limits and potential in terms of performance, complexity and flexibility.

10130-13, Session 6

Multidimensional modulation for next-generation transmission systems *(Invited Paper)*

David Millar, Toshiaki Koike-Akino, Keisuke Kojima, Kieran Parsons, Mitsubishi Electric Research Labs. (United States)

Recent research in multidimensional modulation has shown great promise in long reach applications. In this work, we will investigate the origins of this gain, the different approaches to multidimensional constellation design, and different performance metrics for coded modulation. We will also discuss the reason that such coded modulation schemes seem to have limited application at shorter distances, and the potential for other coded modulation schemes in future transmission systems.

10130-14, Session 6

Characterization of coherent receiver using polarization-multiplexed source generated from coherent transmitter

Qiang Wang, Yang Yue, Massimiliano Salsi, Bo Zhang, Andre Vovan, Jon Anderson, Juniper Networks, Inc. (United States)

Intradyne coherent receiver (ICR) is an essential component for modern coherent systems. Critical parameters of ICR include frequency response, bandwidth, skew, and gain imbalance. Conventionally one creates heterodyne beating between tunable laser source (TLS) and local oscillator, and sweeps frequency of TLS to measure those parameters. A complicated control loop aligns state of polarization (SoP) of TLS to 45/135 degree of principle axis of polarization beam splitter. Otherwise unequal amount of power will launch into two polarizations, leading to inaccurate result.

To overcome this complexity, we present a novel scheme to characterize ICR using polarization-multiplexed laser source generated using internal components of coherent transmitter. The optical signals on two polarizations are modulated with sinusoidal signal at different frequencies. If frequency difference is larger than laser line width, the output at the coherent transmitter is a polarization-multiplexed laser source. This method allows on-board measurement of analog front-end of coherent receiver by connecting coherent transmitter with coherent receiver. Skew between tributaries is first estimated then removed from measurement result. This allows accurate estimation of other parameters. Influence of automatic bias control and radio frequency amplifier is also discussed. Another method is to combine outputs of two separate TLSs with orthogonal polarization through a polarization beam combiner. Both methods lead to robust performance without active control of SoP. The measurement accuracy using polarization-multiplexed laser source is the same as that of the conventional method. The intrinsic resiliency to polarization change leads to simple setup and enables in-field characterization of ICR.

10130-15, Session 6

Stokes-vector direct detection for optical communications *(Invited Paper)*

William Shieh, The Univ. of Melbourne (Australia); An Li, FutureWei Technologies, Inc. (United States); Di Che, Feng Yuan, Hamid Khodakarami, The Univ. of Melbourne (Australia)

The emergence of cloud computing and content distribution networks allows the majority of heave-duty data and signal processing to take place at the dedicated large datacenters . As a result, there is tremendous demand for the cost-effective high-speed interconnects for inter- or intra-datacenter applications. Those interfaces at high speeds of 100 Gb/s and beyond cannot directly adopt the conventional coherent detection which is cost-prohibitive. Neither it can use conventional direct modulation/direct detection (DM/DD) transport due to reach constraint at high transmission rates. This is because fiber chromatic dispersion (CD) introduces severe nonlinear distortion to the signal due to the square-law photo-detection, which limits the transmission distance of DM/DD to tens of kilometers. Furthermore, the phase and polarization domain is not utilized by DM/DD, leading to its low electrical spectrum efficiency (SE). Aiming to improve the electrical SE and extend the transmission distance, advanced DD modulation formats have been proposed through a so-called self-coherent (SCOH) approach, where a carrier is transmitted together with the signal to achieve a linear mapping between the electrical baseband signal and the optical field. In that way, the impact of the CD can be removed from the received signal, greatly extending the transmission distance of the DD system. Particularly, Stokes-vector direct detection (SV-DD) has been proposed to realize linear complex optical channels that yields superior electrical SE and transmission reach. In this talk, we present the principle and discuss the performance of SV-DD modulation format.

10130-16, Session 6

Rigorous study of low-complexity adaptive space-time block-coded MIMO receivers in high-speed mode multiplexed fiber-optic transmission links using few-mode fibers

Yi Weng, Xuan He, Univ. of Louisiana at Lafayette (United States); Junyi Wang, Qualcomm Technologies, Inc. (United States); Zhongqi Pan, Univ. of Louisiana at Lafayette (United States)

Spatial-division multiplexing (SDM) techniques have been purposed to increase the capacity of optical fiber transmission links by utilizing multicore fibers or few-mode fibers (FMF). The most challenging impairments of SDM-based long-haul optical links mainly include modal dispersion and mode-dependent loss (MDL), whereas MDL arises from inline component imperfections, and breaks modal orthogonality thus degrading the capacity of multiple-input-multiple-output (MIMO) receivers. To reduce MDL, optical approaches include mode scramblers and specialty fiber designs, yet these methods were burdened with high cost, yet cannot completely remove the accumulated MDL in the link. Besides, space-time trellis codes (STTC) were purposed to lessen MDL, but suffered from high complexity. In this work, we investigated the performance of space-time block-coding (STBC) scheme to mitigate MDL in SDM-based optical communication by exploiting space and delay diversity, whereas weight matrices of frequency-domain equalization (FDE) were updated heuristically using decision-directed recursive-least-squares (RLS) algorithm for convergence and channel estimation. The STBC was evaluated in a six-mode multiplexed system over 30-km FMF via 6?6 MIMO FDE, with modal gain offset 3 dB, core refractive index 1.49, numerical aperture 0.5. Results show that optical-signal-to-noise ratio (OSNR) tolerance can be improved via STBC by approximately 3.1, 4.9, 7.8 dB for QPSK, 16- and 64-QAM with respective bit-error-rates (BER) and minimum-mean-square-error (MMSE). Besides, we also evaluate the complexity optimization of STBC decoding scheme with zero-forcing decision feedback equalizer by shortening the coding slot length, which is robust to frequency-selective fading channels, and can be scaled up for SDM systems with more dynamic channels.

10130-17, Session 7

Recent advances in low-power CMOS-coherent digital-signal-processing (DSP) technologies *(Invited Paper)*

Osamu Ishida, NTT Electronics Corp. (Japan)

This invited talk reviews recent technology advances in our three generations of low-power CMOS coherent digital signal processor (DSP) implemented with 40, 20, and 16-nm CMOS technologies, with highlights on its functional integration, adaptation, and design optimization for power-efficiency CMOS DSP implementation. The latest 16-nm third-generation (Gen3) DSP implementation achieves sub-10-watt per 100 Gb/s coherent transmission in both 100G DP-QPSK and 200G DP-16QAM transport modes for the first time, and experimentally confirms its trade-off between transmission performance and power dissipations.

10130-18, Session 7

Quadri-correlator-based carrier phase recovery and compensation technique for 100-Gb/s analog domain DP-QPSK coherent optical systems

Rakesh Ashok, Nandakumar Nambath, Anamika Singh, Shivangi Chugh, Shalabh Gupta, Indian Institute of Technology Bombay (India)

To support the huge demand for high speed data in the data centers, the conventional intensity modulation direct detection links is expected to be replaced by coherent optical links using single mode fibers (SMF). These coherent links suffer from phase and frequency offsets between the transmitter and the receiver lasers. Laser linewidth also adds to the non-idealities of the system. A carrier phase recovery and compensation (CPRC) module is used at the receiver to overcome these issues. A CPRC which has a phase detector will be sufficient to nullify the effects of phase error and to overcome the problems caused by laser linewidths. However, a frequency detector is required to cancel out the frequency offset between the transmitter and the receiver lasers. A quadri-correlator based CPRC module comprising phase and frequency detectors is proposed in this work. The module is capable of removing large frequency offsets and of reducing laser linewidth effects. System level simulations show promising results for the frequency offsets of up to 1GHz and linewidths of up to 1MHz when a 100Gb/s dual polarization-quadrature phase shift keying (DP-QPSK) data is transmitted over different lengths of an SMF in the C band.

VPI Transmission Maker is used to model the DP-QPSK optical system. The received signals after O/E conversion for different link conditions are exported to MATLAB in which the proposed architecture is simulated. The basic building blocks used in the proposed CPRC can easily be implemented using analog circuits in ST 130nm BiCMOS technology.

10130-19, Session 7

Evaluation of correlated digital back propagation and extended Kalman filtering for non-linear mitigation in PM-16-QAM WDM systems

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We investigate the individual and combined performance of correlated digital back propagation (CDBP) and extended Kalman filtering (EKF) in mitigating inter and intra-channel non-linearities in wavelength division multiplexed (WDM) systems. The afore-mentioned algorithms are verified through numerical simulations on 28 Gbaud polarization multiplexed (PM) 16-quadrature amplitude modulation (16-QAM) 9-channel WDM system with 50 GHz spacing. A single channel CDBP with one-step-per-span based on asymmetric split step Fourier method (A-SSFM) with optimized non-linear co-efficient has been employed. We also study an amplitude-dependent optimization (AO) of the non-linear co-efficient for CDBP which shows an improvement of approximately 0.4 dB in the Q-factor compared to the conventional optimized CDBP. Moreover, our proposed carrier phase and amplitude noise estimation (CPANE) algorithm based on EKF outperforms AO-CDBP in both linear and non-linear regimes with an enhanced performance besides significantly reduced complexity. We further investigate the combined performance of AO-CDBP and EKF which results in an improved Q-factor at the expense of increased computational cost trading off to the number of required CDBP steps per span. Furthermore, we also analyze the impact of cross phase modulation (XPM) on the combined performance of AO-CDBP and EKF by varying the number of WDM channels. Numerical results show that the obtained gain from employing AO-CDBP prior to EKF reduces with increasing effects of XPM. Additionally, we also discuss the computational complexity of the afore-mentioned algorithms.

10130-20, Session 7

Capacity-approaching transmission based on GMI-optimized modulation formats *(Invited Paper)*

Shaoliang Zhang, NEC Labs. America, Inc. (United States)

Advanced modulation formats are becoming the key factors to further improve system reach and spectral efficiency. Multi-dimensional optimization has been proposed to enhance both receiver sensitivity and tolerance to fiber nonlinearity. However, coded performance of advanced modulation for mats varies depending on the decoding scheme and code design.

In this work, using mutual information and generalized mutual information (GMI) capacity analyses of various modulation formats, it is shown that a signal constellation can be geometrically shaped to approximate an optimal Gaussian distribution with equiprobable signaling, thus approaching the Shannon limit closer than the standard square quadrature amplitude modulation (QAM). By reviewing the design rule of amplitude-phase shifted keying (APSK), Gray-mapping 64APSK is found, being only 0.5dB away at a 8.4 b/s/Hz target spectral efficiency (SE). The bit-mapping-dependent GMI capacity suggests that Gray-mapping 64APSK has more advantage over the other modulation formats, including 4-dim coded modulation and IPM-64QAM. In addition, the relationship between MI and EXtrinsic Information Transfer (EXIT) chart has been studied for various modulation formats to compare the benefits of iterative decoding and Gray mapping.

An experimental comparison verifies that 64APSK is about 0.5dB better than 64QAM at < 9 b/s/Hz 4-dimenional GMI capacity. Using these findings, 168 channels modulated with 24.8Gbaud 64APSK are successfully transmitted over 6375 km using low-density parity check (23090, 16163, 0.7) codes for bit error correction without resource-hungry iterative decoding. A SE of 8.3 b/s/Hz at the total C-band capacity of 34.9Tb/s is achieved using large effective-area and trivial multi-path interference quasi-single-mode fiber after nonlinearity compensation.

10130-21, Session 7

Detection and compensation of power imbalances for DP-QAM transmitter using reconfigurable interference

Yang Yue, Qiang Wang, Bo Zhang, Andre Vovan, Jon Anderson, Juniper Networks, Inc. (United States)

During the past few decades, to meet the ever-growing capacity requirement, several degrees of freedom of photon (time, wavelength, polarization, amplitude, phase, space, and mode) have been used to multiplex electrical data streams. Mature technology is always preferred for industry commercialization. DP-QAM is one of the most promising paths towards 400-Gb/s and 1-Tb/s systems.

A DP-QAM transmitter is typically composed of four tributary channels XI, XQ, YI, and YQ, which are used for in-phase and quadrature modulation of both x- and y- polarizations. In the real implementation, the four tributary channels are typically not identical. This leads to the power imbalances for DP-QAM transmitter, either IQ or XY power imbalance. XY power imbalance is also known as polarization dependent power (PDP). Large uncompensated IQ or XY power imbalance can significantly degrade the performance in the coherent optical communications system. Recently, we have demonstrated a simple scheme for IQ and XY skew detection, potentially with an integrated photodiode. A laudable goal would be to further detect and compensate the power imbalances of all tributary

channels for DP-QAM transmitter with a simple, sensitive, and fast method.

In this work, we propose and experimentally demonstrate a technique to detect and compensate DP-QAM transmitter power imbalances for all four tributary channels. By reconfigurably interfering de-skewed identical BPSK channels, the optical powers of any two tributaries can be balanced by minimizing the output power from their optical interference. Furthermore, the scheme is compatible with variable waveforms, flexible data sequences, and different modulation formats.

10130-28, Session PWed

High precision cross-correlated imaging in few-mode fibers

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The trend of increasing data traffic in conventional communication systems demands utilizing new methods for data transmission, which in combination with traditional techniques, enable overcoming the predicted capacity limit. Mode division multiplexing (MDM), where higher-order modes (HOMs) in a few-mode fiber (FMF) are used as multiple spatial communication channels, comes in this context as a viable approach to enable the optimization of high-capacity links. From this perspective, it becomes highly necessary to possess a diagnostic tool for the precise modal characterization of FMFs. Among existing approaches for modal content analysis, several methods as S2, C2 in time and frequency domain are available. In this contribution we will present an improved time-domain cross-correlated (C2) imaging technique for the experimental evaluation of modal properties in HOM fibers over a broad range of wavelengths. Our modified setup makes it possible to adjust the time resolution of the system according to the needs of the required fiber measurement. We show that by tuning the spectral shape of the source (SuperK EXTREME filtered by SuperK Select), we enhance the time resolution of the system, which allows us to distinguishing differential time delays between HOMs in the picosecond timescale. Broad wavelength scanning in combination with spectral shaping, allows us to estimate the modal behavior of FMF without prior knowledge of the fiber parameters. We performed our demonstration at wavelengths from 850nm to 1100nm which can be easily extended to other wavelengths of interest just by replacing components with the appropriate coating. The method presented here aims to serve as flexible diagnostic tool that can be implemented in MDM systems for judicious evaluation of modal dispersion in FMFs.

10130-29, Session PWed

Modal power distribution transformations in a connector inserted very short-reach multimode optical fiber for mode-group division multiplexing and restricted mode-launching systems

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In very short reach communication systems, such as in-vehicle and in-robots, application of a large-core multimode optical fiber (MMF) has been promising in terms of cost and large connector tolerance. In those fields, modal power distribution (MPD) management to prevent strong mode dispersion is very important, especially in case of data transmission rate compatible with fiber's bandwidth. In that case, restricted mode launching (RML) is valid. In addition to this, a mode group division multiplexing (MGDM) in MMF is drawing attention as potential short-reach multiplexing technique. However, these RML and MGDM systems require the "Total MPD management" from Tx to Rx over the MMF. Especially in those applications, MPD in MMF suffer from not only by propagation length, but also by bending and connector insertion. In order to quantify the MPD transformation, we have already developed a new reproducible representation method, named as Encircled Angular Flux (EAF), and standardized internationally it in IEC. In this paper, we demonstrate the change of measured EAF in MMF and when axis and/or angular misalignment occur at the in-line connector. We implemented measured results to the optical communication system simulator (OptoSim / ModeSYS). Under the 4-PAM and RML condition, for example, 1Gbps data transmission can be achieved by employing the SI-HPCF-MMF with core radius 200um, NA 0.37, and length 40m. EAF representation is a useful I/F parameter to connect optical components in multimode propagation system governed by "Total MPD management". It enables accurate performance prediction considering complex optical propagation peculiar to MMF.

10130-22, Session 8

High-speed digital-to-analog converter concepts *(Invited Paper)*

Christian Schmidt, Christoph Kottke, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany) and Technische Univ. Berlin (Germany); Volker Jungnickel, Ronald Freund, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

The increasing need for high data rates requires the optical networks to advance. For today's communication systems, flexible transmitters based on high-speed digital-to-analog converters (DACs) are desirable. Current fabrication technologies and materials, respectively, used for high-speed DACs are CMOS, Silicon Germanium and Indium Phosphide. For these technologies there is a trade-off between energy-efficiency and bandwidth, e.g. CMOS is highly energy efficient, but the maximum achievable bandwidth is not as high as with SiGe or InP and vice versa.

Next to these trade-offs concerning the fabrication technologies, the bandwidth of the photonic components of today's fiber-optic communication systems, i.e. modulators and photo diodes, is way greater than that of their electrical counterparts, i.e. DACs and analog-to-digital-converters (ADCs). In order to increase the transmission capacity, the bandwidth limitations need to be overcome and hence, new approaches have been introduced into the system design to combine multiple data converters with analog circuitry to a system having a greater sample rate and bandwidth than a single data converter. Two interesting concepts for DACs have been introduced recently: firstly, multiplexing the output of two DACs with an analog multiplexer (MUX-DAC) and secondly, combining multiple signals in the frequency domain using an analog processing system consisting of mixers and filters, i.e. analog bandwidth interleaving (ABI-DAC).

We review the progress and the recent results in the field of high-speed DAC design. Furthermore, we evaluate the above mentioned interleaving concepts regarding their bandwidth enhancement abilities and the associated limitations.

10130-23, Session 8

Toward a low-cost, low-power, low-complexity DAC-based multilevel (M-ary QAM) coherent transmitter using compact linear optical field modulator *(Invited Paper)*

Benjamin B. Dingel, Nasfine Photonics, Inc. (United States)

There is both a continuing trend as well as growing demand to use higher-

order quadrature amplitude modulation (M-ary QAM) formats to increase spectral efficiency (SE), achieve longer transmission reach, and reduces network transmission cost. However, M-ary QAM format requires multilevel input signal instead of the typical binary input signal level which lead to increased component complexity, higher power consumption, and larger footprint size especially for coherent optical transmitters based on purely optical approach using multi-stage configuration. Another general approach which is less complicated is based on an electronic arbitrary waveform generator (AWG)-assisted or digital-to-analog converters (DACs)-assisted optical coherent transmitter using linear field modulator. Although it is encouraging approach, it has drawbacks. In this paper, we present a new type of DAC-assisted QAM coherent transmitter by using a Double-Pass Linear Field Modulator instead of the conventional cascaded modulator configuration. Our design is simpler, consumes half the power, and has half the footprint size compared with standard approach. We will present circuit design concept, compare its characteristic, and discuss its performance tradeoffs.

10130-24, Session 8

A spectrally-efficient linear polarization coding scheme for fiber nonlinearity compensation in CO-OFDM systems

Orappanpara Soman Sunish Kumar, Octavia Dobre, Ramachandran Venkatesan, Memorial Univ. of Newfoundland (Canada); Sarah K. Wilson, Santa Clara Univ. (United States); Oluyemi Omomukuyo, A. Amari, Deyuan Chang, Memorial Univ. of Newfoundland (Canada)

In this paper, we propose a linear polarization coding scheme (LPC) combined with the phase conjugated twin signals (PCTS) technique, referred to as LPC-PCTS, for fiber Kerr nonlinearity mitigation in a coherent optical orthogonal frequency division multiplexing (CO-OFDM) systems. The proposed LPC linearly combines the data symbols on the adjacent subcarriers of the OFDM symbol, one at full amplitude and the other at half amplitude. The linearly coded data is then transmitted as phase conjugate pairs on the same subcarriers of the two OFDM symbols on the two orthogonal polarizations. The nonlinear distortions added to these subcarriers are essentially anticorrelated, since they carry phase conjugate pairs of data. At the receiver, the coherent superposition of the information symbols received on these pairs of subcarriers eventually leads to the cancellation of the nonlinear distortions. Thus, the proposed low-complexity scheme can be effectively used for the fiber Kerr nonlinearity compensation in CO-OFDM system, without spectral efficiency loss. We conducted numerical simulation of a single channel 200 Gb/s CO-OFDM system employing the LPC-PCTS technique. The results show that a Q-factor improvement of 2.3 dB and 1.7 dB with and without the dispersion symmetry, respectively, when compared to the recently proposed phase conjugated subcarrier coding (PCSC) technique, at an average launch power of 3 dBm. In addition, our proposed LPC-PCTS technique shows a significant performance improvement when compared to the 16-quadrature amplitude modulation (QAM) with phase conjugated twin waves (PCTW) scheme, at the same spectral efficiency, for an uncompensated transmission distance of 2800 km.

10130-25, Session 8

Design of XOR/AND gate using 2D photonic crystal principle

Sandip Swarnakar, Santosh Kumar, Sandeep Sharma, Lokendra Singh, DIT Univ. (India)

In this paper, an effective design of all-optical logic gates like XOR gate and AND gate is presented. The structure of these two logic gates is based on T-shape waveguide with optimized silica dielectric rod radius. Along with the two input ports which are essential for the required logical operation, an extra reference input port is used. These two logic gates can be used to construct for various combinational logic circuits, data bit comparison circuits, pattern matching, data encoding and decoding and different switching functions etc.

10130-26, Session 8

Performance and design of an optical FIR filter using slotted ring resonator

Anuj Kumar Sharma, Santosh Kumar, Sandeep Sharma, DIT Univ. (India)

In the recent advancement of communication systems, the device modelling should be designed in such a way that the accuracy, speed, power and cost should meet with the requirement, also the device should be easily adaptable and compatible with the existing systems. In different streams of communication and signal processing, energy efficient, accurate algorithms are built to meet a fully automatic high speed system. In this context, digital filters are used to provide the adequate response to the communication systems because of their linear phase property and the inherent stability. But as far as the speed is concerned, an optical filter plays a vital role in high speed communication environment as It has large bandwidth, greater speed of processing and more efficiency with noise. So an optical ring resonator can be used as an FIR filter to provide the high speed filtering in existing communication system as well as provides enormous bandwidth. A ring resonator can produce arbitrary spectrum output based on transfer function and the performance of this would be measure on the basis of its spectral range (FSR), finesse that is related to the Q-factor, depth of modulation and throughput loss.

10130-27, Session 8

High-bandwidth optical encryption based on temporal optics

Moti Fridman, Bar-Ilan Univ. (Israel)

In many telecommunication systems, the data travels from one point to another in long and unsecured optical fibers. During the travel time of the data in the optical fibers the information can be intercepted or altered.

We present novel technique and device for encrypting optical data traveling in high bandwidth optical channels. Our technique is based on temporal optics and it can encrypt and decrypt optical data in real-time with no latency or bandwidth penalty. We utilized temporal optics based on four wave mixing interaction to encrypt the data before sending it through long optical fibers and similar setup for decrypt the data at the destination.

Our system encrypt the optical signals and not only the data so all the meta-data in the communication system is also encrypted.

We will present theoretical basis, numerical calculation and experimental results of our system. We will also present encryption strength analysis and show that our encryption technique is equivalent for other encryption devices.

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10131-1, Session 1

3D hybrid integration for active silicon photonics *(Invited Paper)*

Jonathan Klamkin, Univ. of California, Santa Barbara (United States)

Despite years of research and development, integrated laser sources remain a bottleneck for silicon photonics (SiPh). Integration of lasers into SiPh can be categorized as hybrid, heterogeneous, or monolithic. Hybrid approaches are the most mature. One example is the co-packaging of lasers with micro-optics and subsequent coupling of laser light to silicon waveguides. More scalable hybrid approaches include butt coupling of lasers and silicon waveguides without the use of micro-optics. This could be accomplished with two chips mounted side by side on a common carrier or by flip-chip bonding of laser chips into recesses adjacent to silicon waveguides. Heterogeneous approaches involve the intimate merging of traditionally incompatible materials and subsequent co-fabrication of these materials to form devices. This approach allows for best-in-class materials selection, however, co-fabrication requires complex fabrication processes. The term monolithic ordinarily refers to a single substrate and materials compatible with the substrate material. Germanium on silicon could be considered a monolithic approach, as could growth of III-V materials (such as indium phosphide (InP) and gallium arsenide) on silicon. This paper summarizes a novel 3D hybrid integration approach that is scalable, low cost, reliable, and that demonstrates superior thermal performance. The approach is based on flip-chip bonding and vertical coupling between InP and silicon waveguides. For the InP waveguide, vertical emission is achieved with a total internal reflection turning mirror. For the silicon waveguide, vertical coupling is achieved with a grating coupler. The InP chip is flip-chip bonded directly to the silicon substrate providing an effective heat sink.

10131-2, Session 2

Data center performance improvement using optical wireless links *(Invited Paper)*

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

The worldwide energy consumption of data centers (DCs) has increased dramatically, now accounting for about 1.5% of US electrical or 1.3% of the world's electricity usage. Nationwide, data centers will be using 139 billion kilowatt-hours by 2020. A significant part of this cooling and information technology devices energy could be saved by shutting down idle servers. This can be achieved by switching workloads from partially loaded servers, and thus allowing additional idle servers to shut down. Workload switching requires additional communication infrastructure such as fiber or optical wireless communication (OWC) links. OWC can be deployed on top the existing cable/fiber network and deployment and maintenance is faster and simpler. OWC also offers dynamic configuration of the network. As well, OWC can be used to augment the performance of load balancing virtualization techniques.

In this talk we will review the main OWC technologies, algorithms concepts and configurations which improve the performance of next generation data centers.

10131-3, Session 2

The role of integrated photonics in datacenter networks *(Invited Paper)*

Madeleine Glick, The Univ. of Arizona (United States)

Datacenter networks are not only larger, but with new applications increasing the east-west traffic and the introduction of the spine leaf architecture there is an urgent need for high bandwidth, low cost, energy efficient interconnects. This paper will discuss the role integrated photonics can have in achieving datacenter requirements. We will review the state of the art and then focus on advances in optical switch fabrics and systems.

The optical switch is of particular interest from the integration point of view. Current MEMS and LCOS commercial solutions are relatively large with relatively slow reconfiguration times limiting their use in packet based datacenter networks. This has driven the research and development of more highly integrated silicon photonic switch fabrics, including micro ring, Mach-Zehnder and MEMS device designs each with its own energy, bandwidth and scalability, challenges and trade-offs. Micro rings show promise for their small footprint, however they require an energy efficient means to maintain wavelength and thermal control. We will review current solutions to thermally control silicon photonics.

Latency requirements have been traditionally less stringent in datacenter networks compared to high performance computing applications, however with the increasing numbers of servers communicating within applications and the growing size of the warehouse datacenter, latency is becoming more critical. Although the transparent optical switch fabric itself has a minimal additional latency, we must also take account of any additional latency of the optically switched architecture. Proposed optically switched architectures will be reviewed.

10131-4, Session 2

Toward exa-scale optical circuit switch interconnect networks for future datacenter/HPC *(Invited Paper)*

Kiyo Ishii, Takashi Inoue, Shu Namiki, National Institute of Advanced Industrial Science and Technology (Japan)

This paper discusses how to realize an optical circuit switching interconnect capable of more than 10 Tbps link bandwidth and more than 100,000 end points scalability. To keep continuous performance improvement of datacenters or high performance computers, high capacity and low latency interconnect network is essential. To handle such large bandwidth interconnect networks with low energy consumption, optical switch technologies will become inevitable. This paper firstly examines the scaling of the energy consumption of optical circuit switching networks related to the network scale, that is, the optical switch port counts, based on the state of the art silicon photonics switch technology. Secondly to achieve Tbps-class link bandwidth, the WDM transmission technology and a shared WDM light source mechanism named "wavelength bank" are introduced. Due to the shared light source, each optical transceiver does not have to carry individual light sources, which enables simple WDM transceivers with cost-efficient silicon photonics technologies. Then a new optical switch control approach which reduces the control overhead time is discussed. In the proposed approach, the optical data plane itself represents the path destination, which enables a simple distributed-like control process. The scalability of the proposed approach is confirmed to support more than 10 Tbps link bandwidth and more than 100,000 endpoints with 40 WDM. One of the features to use optical switches is that it offers direct end-to-end optical paths enabling low latencies. The paper also discusses some of the challenges which should be resolved to practically realize the future large bandwidth optical interconnect networks.

10131-5, Session 3

Universal fibers for data center applications *(Invited Paper)*

Ming-Jun Li, Xin Chen, Jason E Hurley, Jeffery S Stone, Aramais R Zakharian, Doug Coleman, Corning Incorporated (United States)

In data centers, multimode fiber has been the dominant transmission fiber with VCSEL based optical transceivers for system reach mostly less than 100 m. With the emerging hyper-scale data centers, single mode transmission is deployed more frequently to meet the need of longer system reach. Even in large scale data centers, most optical links have short distances, where multimode transmission is more cost effective than single mode transmission. While it is feasible to use both multimode and single mode fibers in data centers, it is desirable to use a uniform type of optical fiber that can accommodate both types of transmissions to simplify fiber cable management, and provide flexibility for future transceiver upgrades.

In this paper, we present a new type of optical fiber, called universal fiber that can be used for both multimode and single mode transmissions. The fiber is a multimode fiber that has an LP01 mode field diameter approximately matched to that of standard single mode fiber. We will present first the universal fiber design concept and discuss design tradeoffs for both single mode and multimode operations. Then we will show actual fibers and their characterizations. Finally, we will present system testing results demonstrating 110 m, 150 m and 2700 m system reach, respectively with 100G SR4, 40G sWDM and 100G CWDM4 transceivers, which matches or exceeds the full system reach set for the respective technology.

10131-6, Session 4

Chip-scale Si-photonics optical transceiver for a photonics-electronics convergence system *(Invited Paper)*

Kazuhiko Kurata, Kenitirou Yashiki, Yasuhiro Ibusuki, Jyunichi Fujikata, Mitsuru Kurihara, Yasuhiko Hagihara, Ichiro Ogura, Takahiro Nakamura, Photonics Electronics Technology Research Association (Japan)

Optical interconnection technology has attracted much attention as high-speed, high-density and energy-efficient solutions. To further apply optical interconnection technologies in shorter reach as board to board and chip to chip regimes, industrial problems such as lowering cost and mass production will be critical issues. Silicon photonics technology employing large-scale wafer level production is expected as one of the solutions. Although highly integrated photonic circuits have been developed, high productivity in optical packaging technologies will be required to fulfill the industry demands of volume and cost. In this viewpoint, single mode optical coupling is one of special difficulty in manufacturing optical wiring systems where less than 1?m alignment accuracy is requested between optical transceiver and optical transmission line. Applying multimode transmission line to silicon photonics technologies is considered to be a practical solution for high productivity packaging. In this paper, we propose high density multi-mode wiring system with chip scale optical Tx/Rx based on silicon photonics.

Called “optical I/O cores,” hybrid-integrated low-power-consumption chip-scale optical transmitters/receivers are newly developed. Low power operation of 5 mW/Gbps/ch has been attained in hybrid-integrated ICs. High speed 25 Gbps/ch error-free transmission has been demonstrated over 300 m MMF in the O band to cover most of reach demands for high performance computers and data centers.?After review of concept of “optical I/O core”, experimental results of multimode fiber transmission are discussed. Finally, its applications and future prospects for photonics-electronics convergence are described.

10131-7, Session 4

Silicon photonic switch technology for optical networks in telecom and datacom areas *(Invited Paper)*

Shigeru Nakamura, Shigeyuki Yanagimachi, NEC Corp. (Japan); Hitoshi Takeshita, NEC Corp (Japan); Akio Tajima, NEC Corp. (Japan)

To support the explosive growth of traffic demand in optical networks in telecom and datacom areas, widespread use of optical switches is highly expected in terms of energy efficiency and flexibility. As a promising platform technology for optical switches, silicon photonics is recently attracting much attention. Major features offered by silicon photonics are compactness and low power consumption with densely integrated devices. Toward practical optical switches, however, basic properties such as low loss, low polarization dependent loss (PDL), and low cross-talk are required, which are still major issues in the field of silicon photonics.

In this paper, we will demonstrate compact 8 ? 8 silicon photonic switch modules with low loss, low PDL, and low cross-talk properties. Demonstrated optical switch modules are intended for applying to ROADMs in telecom optical networks, where optical layer flexibility expressed as colorless, directionless, and contentionless (CDC) capability is highly needed for multi-degree optical network nodes. On an optical switch chip, silicon waveguide circuit including 152 thermo-optical (TO) switch elements for the 8x8 multi-cast switch function and spot size converters (SSCs) for low loss optical coupling to fibers were formed within a chip size of 12 mm x 14 mm. Owing to the developed SSCs, optical coupling between silicon waveguides and fibers was estimated to be 1 dB per facet with polarization insensitive and wavelength insensitive properties. The developed module showed about 6-dB average excess optical loss, including optical coupling loss, on all 64 (=8x8) optical paths. Measured polarization dependent loss (PDL) was about 0.6 dB on average over 64 paths and cross-talk was less than -35 dB. Using these compact optical switch modules, we constructed a TPA prototype featuring over 100-port optical switch subsystem densely mounted on one board and confirmed its feasibility. Under the use in testbeds, we confirmed optical switching of various dual polarization high bit rate signals and fast restoration utilizing 10 us order operation offered by silicon TO switch elements. Port count extendability using multiple compact modules and faster switching capability are also useful for applications in datacenters where hybrid electrical and optical switch network technology is intensively investigated toward higher energy efficiency and lower latency.

10131-16, Session PWed

Model establishing and performance analysis of service stratum traffic in the integrated sensing network

Zhiqun Ge, Ying Wang, Xiaolu Zhang, Yu Zheng, Xinqun Zhao, Xianhan Sun, Southeast Univ. (China)

A time-sharing hybrid-user data flow model scheme based on semi-Markov state-transition algorithm is proposed for multiclass business and service due to the real situation of service stratum traffic in Integrated Sensing Network (ISN). Not only we divide the network traffic into several states: busy, idle and changing, but also the flow variation process has been divided into several time domains accroding to the users' social behavior. For each state and its proper time domain, we analyze it and describe it with an probability density function. Two types of representative business and service: visual sense and auditory sense service are analyzed in this paper. We assume that visual sense service data flow follows a Pareto distribution and auditory sense service data flow follows a lognormal distribution. Besides, the features of the flow arrival interval change with the state. For the visual sense service, the shift of the flow in the busy state is related to the present data rate,so the flow arrival interval follows the lognormal distribution. For the auditory sense service, its flow arrival interval follows

the Poisson distribution according to the VoIP service. In the idle state, the flow can be described by the Weibull distribution. The users' demand in the changing state is less than the busy state, thus the flow arrival interval follows the exponential distribution. The simulation results show that the proposed models achieve reasonable packet loss rate and delay time in the situation of different business and service levels.

10131-8, Session 5

Photonic integrated devices for high-capacity data-center interconnect *(Invited Paper)*

Giovanni B. Farias, CPqD (Brazil); Alexandre P. Freitas, BrPhotonics (Brazil); Yesica R. R. Buscamante, Uiara C. Moura, CPqD (Brazil); Diogo A. Motta, BrPHOTONICS (Brazil); Henrique F. Santana, Andrea Chiuchiarelli, CPqD (Brazil); Luis H. Carvalho, BrPhotonics (Brazil); Jacklyn D. Reis, CPqD (Brazil)

Emerging short-reach data center interconnect (typically in the range of tens of km) is a scenario wherein the capacity has to be maximized over point-to-point optical links without intermediate optical amplification, i.e. unrepeated links. For this application, cost and compactness of the optical transceiver form factor to fit the faceplate density requirement are essential to keep up with the bandwidth demand inside hyper scale data centers.

For the optical module to fit in the current dimensions of client routers without compromise performance both the electronics and the optics have to be efficiently design. As far as the optoelectronic is concerned, photonic integrated circuits (PIC) have been discussed in the community so tha all the photonic functionalities are performed accordingly with the physical dimensions, power budget and performance specifications.

This paper addresses the basic building blocks of optical transceiver, such as optical modulators and receivers, from the design and integration platform perspectives. In the modulator side, two integration platform, namely silicon photonics and polymer on silicon, will be addressed in terms of performance and compactness. In the receiver side, most of the designs using silicon photonics covers the appliction that requires the optical detection of high bandwidth signals.

10131-9, Session 5

Impairment mitigation in noncoherent optical transmission enabled with machine learning for intra-datacenter networks

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Ever-increasing intra-datacenter traffic will spur the introduction of high-baud rates and high-order modulation formats. Increasing symbol rates and modulation levels decreases tolerance against transmission impairment that includes chromatic dispersion. Transmission distance in warehouse-scale datacenters can be several kilometers, and then management of chromatic dispersion is necessary. Dispersion-compensating fibers are widely deployed in backbone networks, however, applying them in datacenters is not cost-effective since wavelength channels are coarsely multiplexed. In digital coherent systems, signal distortion due to chromatic dispersion can be resolved in digital domain; however, it will take long time before coherent systems can be introduced in datacenter networks because of their high cost. In this paper, we propose a novel impairment mitigation method employing machine learning. The proposed method is effective even after non-coherent detection and hence it can be applied to cost-sensitive intra-datacenter networks. The machine learns optimum symbol-decision criteria from a sequence of dispersed training signals, and it discriminates payload signals in accordance with the established decision criteria. With the scheme, the received signals can be demodulated in the presence of large chromatic dispersion. The transmission distance thus can be extended without relying on costly optical dispersion compensation. Since information of transmission links is not a priori required, the proposed scheme can easily be applied to any datacenter network. We conduct transmission experiments using 400-Gbps channels each of which comprises 8-subcarrier 28-Gbaud 4-ary pulse-amplitude modulation (PAM-4) signals, and confirm the effectiveness of the proposed scheme.

10131-10, Session 5

Cost-effective light-emission optical sub-assembly for datacenter networks *(Invited Paper)*

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Cost-effective light-emission optical sub-assemblies (OSAs) are essential for creating high-speed optical interconnections (100, 200, and 400GbE) in datacenter networks, because multiple-optical components are integrated in the light-emission OSA due to wavelength division multiplexing (WDM) or parallel single-mode-fiber x-lane (PSMx). Reducing the number of components, simplifying their testing and assembly process are typical approaches to produce cost-effective OSAs. Silicon photonics (SiP) platform is one of candidates to create them, because it utilizes CMOS technology to reduce the manufacturing, testing, and packaging costs.

In this paper, technologies to create cost-effective light-emission OSA are discussed from the point of view of laser diodes (LDs). There are roughly two solutions for LDs corresponding to cost reduction. One is improving the resistance to operation environment. LDs, with high-back reflection tolerance, and high temperature and humidity tolerance, can reduce optical components such as isolators, and operate with non-hermetic packaging. The other is simplifying the optical assembly. If the LDs and the other optical components such as optical filters and single-mode fibers are passively aligned with lens-free configurations, it is strongly useful to shorten the assembly time. A lens-integrated surface-emitting laser (LISEL), consisting of a DFB laser, an integrated mirror, and an integrated convex lens, has the potential to achieve these requirements. A cost-effective OSA based on the LISEL was proposed and capabilities of an isolator-free operation, non-hermetic packaging, direct and passively aligned optical coupling, and on-wafer testing (OWT) were introduced.

10131-11, Session 5

Ge/SiGe for silicon photonics *(Invited Paper)*

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Our recent progresses are presented in Ge/SiGe near-infrared photonic devices for Si photonics. Ge photodetectors (PDs) with a vertical pin configuration are successfully integrated with Si-based optical waveguides on Si-on-insulator wafers, applying selective epitaxial growth of Ge on Si by chemical vapor deposition. The responsivity more than 0.6 A/W is obtained in the C band together with the electrical bandwidths as large as 20 GHz. High-quality Ge layers lead to the dark leakage current less than 10 nA (10 mA/cm2) at room temperature, and even at the elevated temperature of 100˚C, the dark current is suppressed on the order of 100 nA, being effective for practical applications such as short-reach optical interconnects. Ge/SiGe heterostructures are also presented for the carrier-multiplication layer of low-noise and low-voltage avalanche PDs. In terms of the band engineering for Ge devices, strained SiGe overlayers are discussed as the stressors to control the optical absorption edges in Ge, i.e., a red shift is required for Ge PDs to extend the optical bandwidth towards the L band, while a blue shift is required for Franz-Keldysh electro-absorption optical modulators operating in the C band.

10131-12, Session 6

Systems and technologies for high-speed inter-office/datacenter interface *(Invited Paper)*

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Emerging requirement for short reach links in data center interconnect (DCI) and metro-access transport networks has led to significant R&D on short reach optical interface technologies. Advanced technologies are bringing big changes even in the system and the network architecture for DCI and metro-access transport.

In this paper, we review requirements and technologies for short reach optical interface for DCI and metro-transport network. We introduce the latest technologies with suitable applications and show use cases.

There are two candidates, one is utilization of standardized Ethernet technologies; the other is utilization of digital coherent technologies well known in long haul transmission region. In the first approach, the reach extension of Ethernet is targeted to enhance the transmission performance using standardized Ethernet PHYs. For example, reach extension of the existing Ethernet PHYs using APD receiver instead of PIN-PD receiver, or amplification using C-band instead of O-band channels. This approach will achieve low-cost reach extension with existing Ethernet as it has a high degree of commonality with components used in well-established Ethernet market. Regarding second approach, "Coherent-lite" solution by eliminating functions for long haul transmission and multi-level modulation (16QAM, 32QAM, 64QAM, etc.) enable low-cost/power DSP for short reach transmission. Furthermore, plug & play capability enabled by chromatic dispersion/PMD compensation, fast link recovery and auto calibration function will allow us flexible and low-cost operation. We also describe the integrated use cases of these technologies for both datacom and telecom requirements by referencing the feasibility evaluation results.

10131-13, Session 6

Optically amplified 100-gigabit ethernet *(Invited Paper)*

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Growing data center traffic increases demand for fat data pipes. 100 Gigabit Ethernet is now a common intra- and inter-data center connection technology, and is also being used by some internet exchanges for their largest client connections. 100GBASE-LR4 is an unamplified standard allowing for connection distances up to 10km. Some increase in range over the standard 10km can be reached using APDs in the receiver. But in order to attain the full 40km, optical amplification will be needed. Most commonly, a SOA is added as a receiver pre-amplifier. The channel demultiplexer doubles as an ASE rejection filter. The additional link budget of the amplified solution is on the one hand determined by the gain of the SOA, but at the same time limited by its NF and the lowest per-channel power at the receiver. Amplifier gain tilt over the 15-nm transmission bandwidth as well as polarization dependence are important issues, as is the ability of the system to handle a variety of different link lengths without exceeding the input power at which the amplifier will be saturated. These and other matters will be discussed in detail.

10131-14, Session 7

MPI investigation for 40G NRZ link with low-RL cable assemblies *(Invited Paper)*

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In data centers, high-speed single-mode fiber (SMF) transmission systems are connected by SMFs at multiple points. Reflections at the connection points can cause signal degradation via Multi Path Interference (MPI), and increase in power penalties of BER (Bit Error Ratio) performance. This paper reports testing on consecutively connected low return-loss (19≤RL≤23dB) SC-PC connectors configured in a 40G NRZ SMF transmission line. Low RL connections were created by inserting Polyamide films between connector endfaces; the MPI value was 34.3dB, including both Tx and Rx configurations. Transmission systems of 40G, compliant with VSR2000-3R2 (ITU-TG.693), have spectral line widths of???~3MHz from a 1550nm DFB laser diode. Since the coherent length of the laser diode source is Lc=c/??=100m, it could cause interference at the received power. The calculated power penalty was ~0.15dB for BER~10^-11. The power penalty expected in the BER measurements was not observed; the polarization of the reflected light pulses caused by connectors did not match with outgoing pulses and, therefore, MPI effects were not observed. While the cause is unconfirmed, possible reasons are either (1) NRZ transmission has high resistance to MPI, or (2) the polarization of the reflected light pluses did not match with that of the laser diode output pulses. From this investigation, 40G-NRZ SMF transmission systems are not readily impacted by very low RL connectors, and it is almost impossible for the multiple reflected pulses' polarization to match with that of the output pulses.

10131-15, Session 7

Recent standardization activities for client and networking optical transceivers and its future directions *(Invited Paper)*

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Triggered by the recent vast demands of ICT bandwidth, high speed transmission systems, such as 100G, 200G and 400G, have been developed and installed with extremely high pace. In order to realize these high speed transmission systems, the development of high speed with small form factor optical transceivers is a key issue. De-fact standardization bodies such as IEEE802.3/OIF have played important roles in the industry for leading the proper concepts/designs of the leading edge high speed transceivers. In this paper the latest activities of these standardization bodies for client and networking side are reviewed, and the future migration towards 800G and 1.6T transceivers with low power consumption and small form factor are mainly examined. For these ultrahigh speed transceivers, the concept of integrated devices with low profile and low power consumption, such as using silicon photonics or InP technologies, is very important point from the recent form factor demand, and also the high bandwidth per channel devices, such as 100G/channel and beyond, together with the improvement of CMOS process technology is a key issue to be examined in order to realize 800G and 1.6T transceivers.